

ELECTRICAL ENGINEERING PRACTICE

A PRACTICAL TREATISE FOR ELECTRICAL, CIVIL,
AND MECHANICAL ENGINEERS. WITH MANY TABLES
AND ILLUSTRATIONS

By J. W. MEARES, C.I.E., F.R.A.S.

and

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SERIES PUBLICATION ELECTRICAL ENGINEERING PRACTICE

A PRACTICAL TREATISE
FOR ELECTRICAL, CIVIL, AND MECHANICAL
ENGINEERS

WITH
MANY TABLES AND ILLUSTRATIONS

J. W. MEARES, C.I.E., F.R.A.S.

TELFORD MEDALLIST
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LATE ELECTRICAL ADVISER TO THE GOVERNMENT OF INDIA AND
CHIEF ENGINEER, HYDRO-ELECTRIC SURVEY OF INDIA

AND

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DAVID SALOMONS SCHOLAR, SIEMENS MEDALLIST

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PREFACE TO VOLUME III.

THE appreciative reception of the earlier editions of this work, and the demand for information on subjects which were necessarily omitted from the original single-volume treatment have led to continual enlargement of the book in successive editions. In this, the third (and final) volume of the fourth edition, almost the whole of the material now appears for the first time, and the remainder has been thoroughly revised and largely re-written.

In this volume, Part VI of the complete work deals exhaustively with electric motors and their control, and with the many applications of electrical energy in industrial operations and processes, in traction, in marine propulsion, and in agriculture. Part VII deals with the important subjects of specifications, depreciation, testing and law, the treatment given being supplementary to the rest of the book and such as may best meet the needs of its readers.

Motors, motor control and electric driving are treated very fully from the practical standpoints of principle of operation, available characteristics, and suitable applications. The space given to these subjects has been increased about eight-fold compared with the preceding edition. The chapters on hoisting, agriculture, ship propulsion, and chemical and metallurgical processes are entirely new. In the aggregate these industries may well become more important than the older applications of electricity; already, they fully justify the space allotted to their consideration. The chapters on traction and road vehicles have been thoroughly revised and greatly extended, with particular reference to the great advances in the electrification of main and suburban railways during recent years. The authors are indebted to Mr. Arthur Arnold, A.M.I.Mech.E., for re-writing Chapter 40 (Testing), and to Mr. Chas. B. Clapham, B.Sc., A.M.I.Mech.E., for preparing a large part of Chapter 31 (Hoisting, Conveying, etc.) from the material collected.

Although the scope of the work has been widened so greatly, and

PREFACE TO VOLUME III

the treatment elaborated, a studied effort has been made to deal with every matter in an elementary manner before proceeding to more advanced considerations. Thus, it is hoped, the work will continue to be of value both to students and to consultants who may have to deal with branches of practice with which they are not fully conversant. It is no disrespect to our profession to say that this latter event may, and often does, happen to very eminent engineers. Though this book naturally appeals primarily to readers in the electrical field, the authors happen to know that the volumes already published have been found invaluable by non-electrical engineers, including gas specialists.

In this, as in the preceding volumes, most of the information is based directly upon notes which the authors have had to collect for their own use, and the difficulty they have often experienced in obtaining the desired data and explanations may perhaps form a measure of the utility of the material now presented in collected form. American as well as European practice has been drawn upon freely. Examples have again been freely introduced, and the number of illustrations has been greatly increased. As references are made in places to the *fifth* edition, it should be explained that this edition of Vols. I and II is already in preparation, and that existing paragraph numbers will be retained therein, supplementary paragraphs (e.g. 206A) being added where necessary. In this concluding volume, the index embraces all the three volumes, entries relating to Vols. I and II being set up in different type; and the limiting paragraphs of each volume are printed at the head of each page of this comprehensive index. The same system will be adopted in the fifth edition of the earlier volumes. Both the index numbers and the numerous cross-references indicate *paragraphs* (as shown at the top of the page) and NOT PAGES.

J. W. MEARES.
R. E. NEALE.

7th April, 1933.

EXTRACT FROM PREFACE TO THIRD EDITION.

(N.B.—In reprinting this Preface, those portions which are not in any way applicable to the present edition have been omitted.)

GREATLY during, an endeavour has been made to fill the gap between the many excellent pocket-books of bare data and the highly technical works written for specialists in various branches of electrical engineering. It is believed that the book will appeal to civil, mechanical, and electrical engineers alike; and though the whole field covered cannot be dealt with exhaustively in a single volume, the treatment presented should give the information and guidance meeting the needs of a very wide circle of readers.

Some of the matter presented is quite elementary and, from experience with the previous editions, by no means unnecessary or unappreciated. Even the hydraulic analogy has not been allowed to rest in the place to which it has so often been consigned. One point, in particular, which it helps to bring home to the first-year student is that we use as one of our chief electrical units a *rate*, the ampere, **instead** of the corresponding *quantity*, the coulomb. The irrigation engineer in India has coined the word 'cusec' (1 cubic foot per second) to express a *unit rate of flow* of water, which is exactly analogous to the ampere. Coulombs are seldom mentioned in practical electrical engineering, and the average engineer undoubtedly regards the coulomb in a roundabout way as an ampere-second—a multiple of a rate by a time—instead of as a definite quantity in itself. Even where ampere-hours are mentioned the electrical engineer often forgets that this larger unit of quantity would be one of the primary units in other branches of engineering, equivalent (say) to a gallon of water. Conceptions such as a yard or a gallon offer no difficulty to any intelligent being, but every one must have met with persons completely lacking in the geometrical sense, to whom an angle meant absolutely nothing. Further up the scale difficulty is experienced in explaining such compound terms as 'pounds-feet' or 'feet per second per second,' and

EXTRACT FROM PREFACE TO THIRD EDITION

when we arrive at the maximum demand system of charging for electrical energy, the average man frankly gives up attempting to grasp its significance. If, then, the explanation in this book appears at times too elementary, it is a lapse in the right direction.

It has been the author's aim to be severely practical: hence many terms used in electrical literature find no place in this volume, either because the reader will not need them in his daily work or, in so far as they deal with the elements of electricity and magnetism, because they are assumed to be already known to him. Where a term is used which has not so far been defined, the explanation will be found on a later page, and, in the absence of a forward reference, the index will guide the reader. Where definitions of terms are given, they are complete and for the most part accepted internationally; but it does not follow that they are self-explanatory in every case.

Practical examples have been used freely for the purpose of illustration, no amount of mere description being so effective in explaining rules and formulæ. For the same reason, diagrams of strictly utilitarian nature have been used to show plainly the connections and so forth described in the text. The examples chosen all make use of British standard frequencies, pressures, etc., and numerical results are those obtained by using the slide rule and omitting unnecessary figures. It is still often overlooked that the accuracy of any result is limited by that of the measurements and data which yield it; and that, whereas half a dozen significant figures may be accurate and necessary in scientific work, an accuracy to within even 1 per cent. is only accidental where commercial calculations or measurements with commercial instruments are concerned.

Pains have been taken to make the index as complete as possible, and it should be noted that cross references and index references are to PARAGRAPHS, and that *paragraph numbers are shown at the head of pages* and page numbers at the foot.

J. W. MEARES.

LONDON, 21st September, 1916.

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Abbreviations for Names of Units; to be used only after Numerical Values.

Name of Unit.	Abbreviation.*	Name of Unit.	Abbreviation.*
Ampere	A	Volt-coulomb	VC
Volt	V	Watt-hour	Wh
Ohm	Ω	Volt-ampere	VA
Coulomb	C	Ampere-hour	Ah
Joule	J	Milliampere	mA
Watt	W	Kilowatt	kW
Farad	F	Kilovolt-ampere	kVA
Henry	H	Kilowatt-hour	kWh

m for milli-

k for kilo-

μ for micro- or mier-

M for mega- or meg-

Other abbreviations used in this book are as follows:

Inch	in.	Board of Trade Unit (or Kelvin)	B.T.U. or unit
Foot	ft.	Standard wire-gauge	S.W.G.
Yard	yd.	Home Office	H.O.
Mile	mi.	Board of Trade	B.O.T.
Metre	m.	International Electro-technical Commission	I.E.C.
Kilometre	km.	British Standards Institution, British Engineering Standards Association, B.E.S.A.	B.S.I.
Centimetre	cm.	British Standard Specification	B.S.S.
Millimetre	mm.	Electricity Commissioners, publications of	E.L.C. No.
Square	sq.	Institution of Electrical Engineers	I.E.E.
Cubic	cu.	British Electrical and Allied Manufacturers' Association	B.E.A.M.A.
Gramme	gm.	British Electrical and Allied Industries Research Association	B.E.R.A.
Kilogramme	kg.		
Continuous or direct current	C.C. or D.C.		
Alternating current	A.C.		
Positive pole	+		
Negative pole	-		
Neutral, D.C.	\pm		
Neutral, A.C.	N.		
Earth	E.		
Horse-power (indicated or brake)	I.H.P.; B.H.P.		
Electrical horse-power	E.H.P.		
Power factor	P.F. or cos ϕ .		
Maximum Demand	M.D.		
British Thermal Unit	B.Th.U.		

*The I.E.C. recommends that these abbreviations should be in heavy faced type, but for economy in printing, and following the practice adopted in the *I.E.E. Journal* and in the technical press, ordinary type is used for them throughout this book.

†The letters O and Ω are recommended provisionally. Ω is used in this book because O is liable to be confused with the numeral zero. The letter Ω should no longer be used for megohm.

ELECTRICAL ENGINEERING PRACTICE

PART VI. (*contd.*).—APPLICATIONS OF ELECTRICAL ENERGY.

CHAPTER 28.

ELECTRIC MOTORS.

669. General Principles of Electric Motors.—An electric motor is a machine for converting electrical power into mechanical power, *i.e.* the reverse of a generator (§ 132, Vol. 1). When supplied with electrical energy, whether direct current or single-phase, 2-phase, or 3-phase alternating current, it will deliver mechanical power at the pulley or shaft. The two main groups are D.C. motors and A.C. motors, according to the nature of the electrical energy used, and in each of these main groups there is a number of different types of motors with widely varying characteristics. By selecting a suitable type of motor and a suitable method of control, it is possible to obtain almost any desired relation between speed and torque, these being the two factors determining the mechanical output of the motor (Horse-power = $2\pi \times \text{Torque (ft.-lb.)} \times \text{R.P.M.} / 33\,000$). The principles of operation and the electromechanical characteristics of motors are considered in this chapter; the starting and control of motors in Chapter 29; and the selection and application of motors to electric driving in Chapter 30.

As explained in § 132 (Vol. 1), when a conductor lying in a magnetic field is traversed by an electric current, the conductor is subjected to a mechanical force which tends to move it across the field.* In the usual form of direct current motor the main

* The relation between the directions of field, armature current and motion in a motor may be determined by Fleming's rule (§ 35, Vol. 1): Extend the forefinger and thumb of the *left* hand at right angles to each other, and bend the middle finger at right angles to the plane containing the forefinger and thumb. Then, if

field (as distinct from the field due to the current in the armature conductor, Fig. 245) is provided by a stationary system of electromagnets, with 2, 4, 6, etc., poles, as the case may be, inside which there is a cylindrical armature carrying insulated wires on its periphery. When electric current is sent through these wires, the force on each conductor tends to rotate it (and therefore the armature core and shaft to which it is attached) about the centre line of the machine. A commutator (§ 132, Vol. I) periodically reverses the direction of flow of the current in the armature conductors at the moments required to maintain continuous rotation of the armature.

Referring to Fig. 245 which shows, for simplicity, a bipolar magnet (field coils omitted) and a single armature coil, the addition of the main field and conductor field at a , and their mutual neutralisation at b , results in the armature being driven by the forces F in the direction of rotation indicated by the arrow M . From the explanation given in § 132, Vol. I, it will be understood that the rotation of the conductor in the field due to NS results in the generation of an E.M.F. in the conductor which is termed a back-E.M.F. (E_b) because it opposes the applied E.M.F. The effective E.M.F. in the conductor is the difference between the applied and back E.M.F.'s, *i.e.* $E - E_b$ volts, and this divided by the resistance R ohms of the armature coil gives the value I amperes of the current flowing through the latter, *i.e.* $I = (E - E_b) / R$.

When the armature is stationary the back-E.M.F. is zero, hence the current flowing through the armature coil is E / R at this moment. The resistance R is very low (often a fraction of an ohm), so that it is usually necessary to connect an external resistance in series with the armature during the starting period, in order that the current may be kept to a reasonable value (Chapter 29). Directly the armature begins to rotate, a back-E.M.F. is generated in its winding and, as long as the field is constant, this back-E.M.F. increases in direct proportion to the speed. The starting resistance is removed progressively as the machine accelerates and, at or near full speed, the armature is

the forefinger be set along the direction of the magnetic field, and the middle finger along the direction of the armature current, the thumb indicates the direction of motion: whence the mnemonic: FORefinger, FORee; mIddle finger, current (I); thUMb, Motion.

ultimately connected straight across the supply mains. The motor then runs at such speed that the difference between the applied E.M.F. and the back-E.M.F. is just enough to send through the armature the current required to keep the motor running at this speed.

The torque developed by the motor is proportional to the product of the field strength by the armature current. In

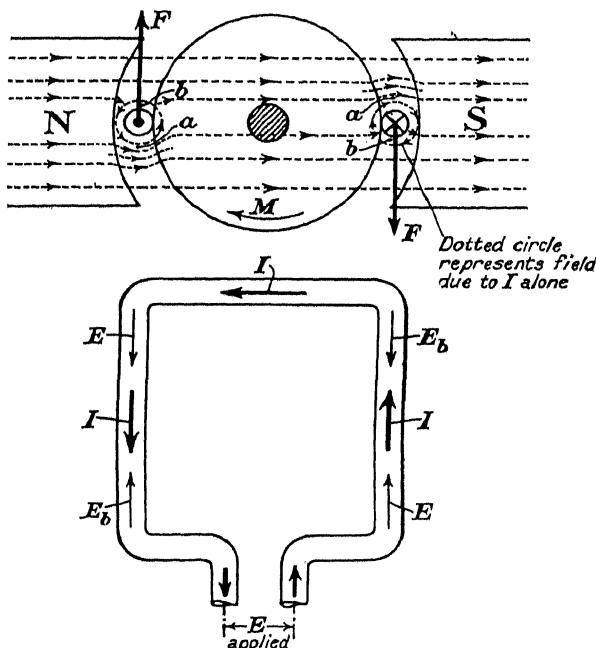


FIG. 245.—Diagrammatic representation of the action of an electric motor; assuming the armature core to be non-magnetic.

(NOTE: \times indicates current flowing away from, and \bullet towards the observer.)

the shunt-wound D.C. motor (§ 675) the coils exciting the field magnets are shunted across the supply mains so that, apart from changes introduced deliberately (*e.g.* by the insertion or removal of resistance) or by certain subsidiary causes discussed later, the strength of the field remains constant, whatever the value of the armature current. In the series-wound D.C. motor (§ 676), however, the field coils are in series with the armature winding so that, until magnetic saturation of the field core is approached

(§ 81, Vol. 1), the strength of the field varies proportionately with the armature current. These distinctions result in the shunt and series motors having very different characteristics, which are discussed more fully in §§ 675, 676. For the present, the characteristics of each may be summarised as follows:

(1) The shunt motor has a constant field and runs at nearly constant speed whatever the load. As the load increases, demanding a heavier torque, the armature current must increase proportionately to the torque (the field being constant). This, however, involves only the small decrease in speed needed to reduce the back-E.M.F. far enough to permit $(E - E_b)$ to send the higher current through the armature resistance.

For example, suppose that a 50 H.P. shunt wound motor, partially loaded, takes 60 A at 500 V and runs at 400 r.p.m. Suppose that the field current is 2.5 A, then the armature current is $(60 - 2.5) = 57.5$ A. If the effective resistance of the armature is 0.2 Ω , then, since $I = (E - E_b) / R$, we have: $57.5 = (500 - E_b) / 0.2$, whence $E_b = 488.5$ V. If now the load on the motor is increased to such an extent that the current rises to 85 A, the armature current $I = 85 - 2.5 = 82.5$ A (the field current remaining constant). Hence $82.5 = (500 - E'_b) / 0.2$ whence $E'_b = 489.5$ V. In other words, the back-E.M.F. has only to decrease by $488.5 - 489.5 = 1$ V in order to allow the heavier current to flow through the armature, and since $E_b = 488.5$ V was generated at 400 r.p.m., the lower $E'_b (= 489.5$ V) will be generated at $488.5 \times 400 / 489.5$ or 399 r.p.m., the field being constant. Thus, increasing the load on the motor by about 47% results only in 4 r.p.m. (or 1%) decrease in speed. The field being constant, the torque varies directly with the armature current.

(2) The series motor has a field which increases with the armature current and therefore with the load. Neglecting magnetic saturation, doubling the armature current results in four times the torque (for the field strength is also doubled). In order that the armature current may rise, the back-E.M.F. must fall, and, since the field has been doubled, the speed must fall to less than half its original value. The speed of the series motor thus falls quickly with increasing load and, conversely, at light load the machine 'races' at dangerously high speed, for, the armature current being low, the field is also weak and a very high speed is needed to generate the high back-E.M.F. needed to keep the armature current low.

For example, suppose that a 50 H.P. series-wound motor, partially loaded, takes 60 A at 500 V and runs at 400 r.p.m. Suppose, also, that the total effective resistance of the armature and field windings is 0.55 Ω , then, since $I = (E - E_b) / R$, we

have: $60 = (500 - E'_b) / 0.55$, whence $E'_b = 467$ V. If now the load be increased so that the motor takes 85 A at 500 V, we have: $85 = (500 - E'_b) / 0.55$, whence $E'_b = 453$ V. Neglecting the effect of magnetic saturation (which, in practice, causes the field strength to increase less rapidly than the exciting current, *see* § 81, Vol. 1), the field is 85 / 60 times as strong as it was originally, hence $E'_b = 453$ V is generated at a speed $= 400 \times \frac{60}{85} \times \frac{453}{467} = 274$ r.p.m. (In practice, a higher speed would be required, owing to the above-mentioned effect of magnetic saturation.) Thus, in this example, increasing the load by about 42 % results in 126 r.p.m. (or about 31.5 %) decrease in speed. Also, since the field increases with the armature current, the torque varies with the square of the latter (neglecting saturation).

The preceding examples show clearly the inherent distinctions between the characteristics of shunt and series-wound D.C. motors (*see also* §§ 675, 676), distinctions which are so definite and important that it is usual to say that an A.C. commutator motor has 'shunt characteristics' or 'series characteristics,' according as its load-speed curve resembles that of a shunt-wound or series-wound D.C. motor. Intermediate between shunt and series characteristics there are 'compound characteristics' resembling those of a D.C. motor which has both shunt and series field coils; the reasons for and effects of compound excitation are explained later (§ 677).

As reversing the polarity of supply to a D.C. motor, by interchanging the supply leads, does not reverse the direction of rotation (the direction of the field and the direction of the armature current being both reversed, so that the torque remains as before), there is, in principle, no reason why a D.C. motor should not be operated on A.C. supply. Certain small motors, appropriately known as 'universal' motors (§ 710), are actually supplied for use on D.C. or A.C. supply of any commercial frequency; and traincar motors are sometimes designed to work on either D.C. or A.C. supply, the former being used in urban and the latter in interurban districts. With these exceptions, however, shunt- and series-wound motors must be built specially for A.C. operation to allow for the different characteristics of the iron-cored windings when carrying A.C., and to take account of transformer action. Apart from A.C. commutator motors, which may be regarded as D.C. motors modified to suit A.C. working, there are motors which are specifically A.C. types and cannot be operated on D.C. supply; e.g. the synchronous motor (§ 679) in which a rotating field produced by a stationary polyphase winding 'locks' with and pulls round an electromagnet

excited by direct current, and the induction motor § 681, in which the driving torque is due to the pulsating or rotating field of an A.C. stator winding and the currents which this field induces in the rotor.

By using one or other of the many types of A.C. motors described later in this chapter it is possible to duplicate very closely the characteristics of D.C. motors, but the latter are generally simpler and cheaper where continuous speed regulation is required over a wide range. The A.C. induction motor is already the most commonly employed of all electric motors and, with the increasing use of A.C. in distribution networks (Chap. 20, Vol. 2), the predominance of A.C. motors is certain to increase. Nevertheless, D.C. motors are not likely ever to be entirely superseded; many industrial consumers operate private converting plant in order to be able to use D.C. motors where the characteristics of the latter are specially desirable.

670. British Standard Types and Ratings for Electric Motors.*—The 'types' here considered are not the distinctive kinds of motors, e.g. D.C. series-wound, D.C. shunt-wound, A.C. synchronous, A.C. induction, etc., but the headings under which motors are classified by British Standard Specifications † according to (1) their horse-power per r.p.m. (or per 1 000 r.p.m.); (2) the type of their enclosure; (3) the relation between their load and speed; and (4) whether the rating ‡ permits a sustained overload or is a continuous maximum rating, or a short-time rating.

(1) HORSE-POWER PER R.P.M. (OR PER 1 000 R.P.M.). This is obviously a classification on the basis of torque, for

$$\text{H.P.} = 2\pi \times \text{Torque (ft.-lb.)} \times \text{r.p.m.} / 33\,000$$

* The reader is asked to note that this paragraph replaces § 186, Vol. I (4th edition), in so far as the ratings of fractional H.P. motors, industrial motors and generators, and large generators and motors are concerned.

† Issued by the British Standards Institution (formerly the British Engineering Standards Association), 28 Victoria Street, London, S.W. 1. The extracts from, and the notes based on these Specifications throughout this book are intended only for general information. It is neither possible nor desirable to quote extensively from the Specifications. The latter are inexpensive (mostly 2s. each) and, as they are subject to periodic revision, it is essential that the complete and latest text be consulted in order to ensure compliance with British Standard practice.

‡ The *rating* of an electrical machine is the output assigned to it by the maker together with the associated conditions marked on the Rating Plate.

hence

$$\frac{\text{H.P.}}{\text{r.p.m.}} = \frac{2\pi}{33\,000} \times \text{Torque (ft.-lb.)}$$

and

$$\begin{aligned}\text{Torque (ft.-lb.)} &= \frac{33\,000}{2\pi} \times \frac{\text{H.P.}}{\text{r.p.m.}} = 5\,250 \times \text{H.P. per r.p.m.} \\ &= 5.25 \times \text{H.P. per 1\,000 r.p.m.}\end{aligned}$$

The British Standard Specifications (B.S.S.) relating to electric motors distinguish between fractional horse-power motors, industrial motors, and large motors as follows:—

B.S.S. No. 170—1926: Fractional Horse-Power Motors.—This specification applies to motors of *any continuous rating less than 1 H.P. per 1 000 r.p.m.* having windings insulated with Class A or Class O material.* It applies to D.C. and to A.C. motors of commutator and induction type, but not to 'universal' motors (*i.e.* motors capable of operating on both A.C. or D.C. circuits).

[NOTE: 1 H.P. per 1 000 r.p.m. corresponds to a torque of about 5.25 ft.-lb.; see formula above.]

B.S.S. No. 168—1926: Industrial Electric Motors (and Generators †).

This specification applies to machines of *continuous rating equal to or exceeding 1 H.P. per 1 000 r.p.m. but not exceeding 2 B.H.P. per r.p.m.*, having windings insulated with Class A material,‡ wound for voltages not exceeding 7 000 V. It does not apply to traction motors (*see* B.S. Specification, No. 178), or to machines with flame-proof enclosure (*see* B.S. Specification No. 270, 'Electric Motors and Generators for Mines').

[NOTE: 1 H.P. per 1 000 r.p.m. corresponds to a torque of about 5.25 ft.-lb.; and 2 B.H.P. per r.p.m. corresponds to about 10 500 ft.-lb.; see formula above.]

B.S.S. No. 169—1925: Large Electric Motors (and Generators §): Rating Permitting Overloads.—This specification is based upon a rating which is such that a

* The following classification of insulating materials was adopted by the International Electrotechnical Commission, in April, 1926:—

Class O.—Cotton, silk, paper, and similar organic materials when neither impregnated nor immersed in oil.

Class A.—Cotton, silk, paper, and similar organic materials when impregnated or immersed in oil; also enamelled wire.

Class B.—Mica and asbestos and similar inorganic materials in built-up form combined with binding cement.

Class C.—Mica without binding cement, porcelain, glass, quartz, and other similar materials.

For details, particularly concerning combinations of insulating materials belonging to different classes, *see* B.S. Specification, No. 168—1926, Appendix I.

† Clauses relating specifically to generators are not considered here.

‡ See footnote to No. 170 above.

§ See footnote to No. 168 above.

sustained overload * may be carried by the machine after it has attained its steady temperature corresponding to its rated load (cf. No. 226 below). It applies to motors of which the maximum sustained output (i.e. the rated load plus 25% overload in torque for 2 hrs.) does not exceed $2\frac{1}{2}$ B.H.P. per r.p.m., having windings insulated with Class A and Class B materials,† but excluding single phase motors and traction motors.

[NOTE: $2\frac{1}{2}$ B.H.P. per r.p.m. corresponds to a torque of about 13.125 ft. lb., see formula above.]

U.S.S. No. 226—1925: *Large Electric Motors (and Generators): Continuous Maximum Rating.* This specification is based on the rating at which the machine may safely be run continuously, provided no sustained overloads * are thrown upon it (cf. No. 169 above). It applies to motors rated for more than $2\frac{1}{2}$ B.H.P. per r.p.m., having windings insulated with Class A and Class B materials,‡ but excluding single phase motors and traction motors.

(2) TYPES OF ENCLOSURE OF MACHINES. The types of enclosure recognised by the above-mentioned B.S. Specifications may be briefly defined as follows. It should be noted that many of these types of enclosure are not used for fractional horse-power motors.

(a) OPEN MACHINES.

Open Motor.—One with no restriction to ventilation other than that necessitated by good mechanical construction.

Open Pedestal Motor.—An 'open motor' (q.v.) with pedestal bearings supported independently of the machine frame.

Open End-Bracket Motor.—An 'open motor' (q.v.) with end brackets of which the bearings form an integral part.

Protected Motor.—The internal rotating parts and live parts are protected mechanically from accidental or careless contact while ventilation is not materially obstructed. Unless otherwise specified, a protected machine has end bracket (end shield) bearings.

Screen-Protected (formerly called Enclosed Ventilated) Motor. Ventilating openings in the frame and end shields are protected with perforated covers (wire screen, expanded metal, etc.) having apertures not exceeding $\frac{1}{4}$ sq. in. but not less than $\frac{1}{16}$ sq. in. in area.

* *Overload* is any load in excess of the Rated Load.

Sustained Overload is an overload sustained long enough to affect appreciably the temperature of the machine.

Momentary Overload is an overload not sustained long enough to affect appreciably the temperature of the machine.

In practice, the period (if any) for which an electric motor can carry a sustained overload is determined by the heating of the machine; whereas the momentary overload capacity is determined by the limits of satisfactory commutation in D.C. and A.C. commutator motors, and by the stalling torque in the case of A.C. synchronous and induction motors.

† See footnote to No. 170 above.

‡ See footnote to No. 168 above.

§ See footnote to No. 170 above.

Motors with Fine Mesh Covers.—Machines having mesh openings smaller than $\frac{1}{8}$ sq. in. in area. Such machines are to be regarded as 'totally enclosed motors' (q.v.) and are to be tested (as regards temperature rise, etc.) with the openings closed, as such openings often become clogged in service.

Drip-Proof Motor.—One having a frame and end shields provided with openings for ventilation so protected as to exclude falling water or dirt.

(b) PIPE- OR DUCT-VENTILATED MACHINES.

Pipe-Ventilated or Duct-Ventilated Motor.—A machine in which there is a continuous supply of fresh ventilating air, the frame being so arranged that the air may be conveyed to and (or from the machine) through pipes or ducts attached to the enclosing case. Provision may be made for either an inlet or an outlet duct or for both. The supply of cooling air may be maintained by self ventilation, by forced draught (external pressure), or by induced draught (air drawn through the machine by external means).

The ducts to be provided and the means of maintaining air flow should be specified.

Forced-Draught Motor.—A 'pipe-ventilated motor' (q.v.) with ventilating air supplied under pressure by means external to the machine itself.

Induced-Draught Motor.—A 'pipe-ventilated motor' (q.v.) with ventilating air drawn through the machine by means external to the machine itself.

(c) TOTALLY ENCLOSED MACHINES.

Totally Enclosed Motor.—One so enclosed as to prevent circulation of air between the inside and outside of the case, but not sufficiently to be termed 'air tight.'

Totally-Enclosed Air-Blast Self-Cooled Motor.—The cooling is augmented by a fan, driven by the motor itself, blowing external air over the cooling surfaces and (or through) the cooling passages, if any.

Totally-Enclosed Air-Blast Separately-Cooled Motor.—The same as a totally-enclosed air-blast self-cooled motor except that the fan is separately driven.

Totally-Enclosed Water-Cooled Motor.—The cooling is augmented by water-cooled surfaces embodied in the machine itself.

Totally-Enclosed Closed-Air-Circuit Motor.—Special provision is made for cooling the enclosed air by passing it through a cooler (air-draught, water or other type) external to the machine.

Flame-Proof Motor; and Motor with Flame-Proof Slip Ring Enclosure.—These machines are dealt with in B.S.S. No. 270—1930, 'Electric Motors and Generators for Mines'; see also B.S.S. No. 229, 1926, 'Flame-Proof Enclosures for Electrical Apparatus and Tests for Flame-Proof Enclosures.'

A flame-proof enclosure (including explosion-proof) is one capable of withstanding any explosion of gas that may occur inside it, while preventing the ignition of any inflammable gas outside it. If the casing encloses the whole motor we have a 'flame-proof motor'; but if it encloses only the slip rings we have a 'motor with flame-proof slip ring enclosure.'

The main requirements of B.S.S. 270—1930, regarding *flame-proof joints* may be summarised as follows:—

All joints in a flame-proof enclosure shall be flanged joints; and no rubber, asbestos or any material liable to deterioration shall be used to pack joints. In close metal-to-metal flanged joints the width of the flange across the joint must be at least 1 in.; bolt holes may be ~~disregarded~~ provided that the inner edge of the

hole is at least $\frac{1}{8}$ in. from the inner edge of the flange. With careful construction, pressure relief may be obtained by: (1) flanged joints with a gap which need not exceed 0.02 in., even under internal pressure, and may not be reduced to a gap to prevent pressure relief by the omission of any part after dismantling; the cover should be close for at least $\frac{1}{8}$ in. radially round test hole. The path for gas escaping between flanges should be at least 1 in. in length. (2) Pressure relief vent other than flange gaps; these include perforated plates, multiple screw and stud, and spring loaded bolts and valves.*

In addition to the above terms, the following are commonly used, and definitions of them are included in American rules:

Moisture-Resisting Motor. One in which all parts are treated with moisture-resisting material so that the motor can be used in very humid situations.

Submersible Motor. Capable of withstanding complete submersion in fresh or sea water, whether idle or working.

(3) RELATION BETWEEN LOAD AND SPEED. The inherent variations in the speed of a motor and the possibility of deliberately changing the speed are distinctive characteristics of great practical importance. Unfortunately, the terms used to classify motors on this basis are often employed loosely. British Standard definitions and American equivalents are as follows:

Change-Speed Motor (U.S.A. equivalent: *Multi-Speed Motor*). A motor which can be operated at any one of several distinct speeds, each practically independent of the load; e.g. a motor the speed of which is varied by changing the number of its poles.

Variable Speed Motor (U.S.A. equivalent: *Adjustable Speed Motor*). A motor the speed of which can be varied gradually over a specified range but which, when once adjusted, remains practically unaffected by the load; e.g. a shunt motor designed for a range of speed variation.

Inverse Speed Motor (U.S.A. equivalent: *Varying Speed Motor*). A motor the speed of which decreases when the load increases; e.g. a series wound or heavily compound-wound motor.

(4) RATING AND LIMITS OF TEMPERATURE RISE. British Standard classes of rating for electric motors are:

(a) *British Standard Continuous Rating*, defining the load which can be carried on test, under the conditions of the rating and of the B.S. Specification relating to the class of motor concerned, for an unlimited period without exceeding the limits of temperature rise given in the B.S. Specification concerned.

(b) *British Standard Short-time Rating*, defining the load which can be carried on test for a specified time (1 hr., $\frac{1}{2}$ hr., or $\frac{1}{4}$ hr., as the case may be) without exceeding the limits of temperature rise given in the relevant B.S. Specification, the test being started with the motor cold.

* See Part V, B.S.S. 270; also *Safety in Mines Research Board Papers*, Nos. 5, 21, 35; H.M. Stationery Office (§ 848).

It is further required that *change-speed motors* shall have a definite rating for each speed; and that *variable speed motors* shall have a definite rating for each of the limiting speeds specified.

In the case of generators rated for two limits of voltage, the rated current and output shall be determined at the higher voltage unless otherwise specified.

The following clauses are an *unofficial* summary of the ratings and limits of temperature rise given in B.S. Specifications relating to the motors stated (*see also* (1) HORSE-POWER PER R.P.M. above).

General.—Except in the case of Fractional Horse-power Motors (which, under B.S.S. No. 170—1926, are only suitable for use at altitudes not exceeding 3 800 ft. above sea-level), it is necessary to reduce the limits of temperature rise given in Tables 109, 110, 112 by $1\frac{1}{2}\%$ for each 1 000 ft. above sea-level in the case of machines tested near sea-level but intended for service at altitudes between 3 800 and 10 000 ft.

No correction should be made in the observed temperature rise in those cases where the temperature of the cooling air during the test is different from that expected in service. The standard ratings are based, however, on the assumption that the temperature of the cooling air will not exceed 40°C .

The temperature test of a machine having a short-time rating shall commence when the temperature of the windings is the same as that of the cooling air, and it shall continue for the time required by the rating. The duration of the temperature test on a continuous-rating machine shall be such that sufficient evidence is obtained to show that the temperature rise would not exceed the specified limits if the test were prolonged until a steady temperature was reached. When a machine has more than one rating, the temperature test must be at that rating which produces greatest temperature rise.

Fractional Horse-power Motors (Continuous Rating less than 1 H.P. per 1 000 r.p.m.)—According to B.S.S. No. 170—1926, the *continuous rating* of these machines is the load which can be carried for an unlimited period, and the *short-time rating* is the load which can be carried for $\frac{1}{2}$ hr. (*half-hour rating*) or $\frac{1}{4}$ hr. (*quarter-hour rating*) without exceeding the limits of temperature rise given in Table 109. Motors rated in accordance with this Specification must be able to carry without injury and without injurious sparking the following excess torque, after reaching the temperature corresponding to continuous operation at rated load:—

(a) *Continuous-Rating Motors: D.C., 3-ph. A.C. and 1-ph. Commutator Motors (excluding 1-ph. induction motors and propeller blade fan motors).*— 25% excess torque for 5 mins.

(b) *Short-time Rated Motors, and Continuous-Rating 1 ph. Induction Motors and motors coupled to fans of the propeller blade type.*—No excess torque.

Machines rated in accordance with this Specification are suitable for use in temperate climates and at altitudes not exceeding 3 800 ft. above sea-level.

The tolerance on the speed of these motors above or below guaranteed speed at rated load and at the temperature corresponding to rated load is $\pm 12\frac{1}{2}\%$ for motors with shunt characteristics; $\pm 15\%$ for series-characteristic motors of less than 1 B.H.P. but not less than $\frac{1}{2}$ B.H.P. rating at 1 000 r.p.m.; and $\pm 20\%$ for series-characteristic motors below $\frac{1}{2}$ B.H.P. rating at 1 000 r.p.m.

The high-voltage tests to be applied to these motors are noted in § 1018.

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TABLE 109. *Limits of Temperature Rise for Fractional Horse-Power Motors (when tested in accordance with B.S.S. No. 170 1926).*

Part of Motor.	Temperature Rise Measured by Thermometer			
	Motors (other than totally enclosed and drip-proof) with Continuous Rating.		Motors with Short-Time Rating, and all Totally Enclosed and Drip-Proof Motors.	
	Class A. Material.*	Class B. Material.*	Class A. Material.*	Class B. Material.*
	°C.	°C.	°C.	°C.
Insulated windings, and cores in contact with them; also bearings	40	25	50	35
Commutators and slip-rings	45	30	55	40
Uninsulated parts, and cores not in contact with insulated windings.	Nowhere such that there is risk of injury to insulation on adjacent parts.			

Industrial Electric Motors and Generators (Continuous Rating from 1 H.P. per 1 000 r.p.m. to 2 B.H.P. (or kW, or kVA) per r.p.m. inclusive). According to B.S.S. No. 168—1926, the *continuous rating* of these machines is the load which can be carried for an unlimited period, and the *short-time rating* is the load which can be carried for 1 hr. (*one hour rating*) or $\frac{1}{2}$ hr. (*half-hour rating*) without exceeding the temperature rise specified in Table 110.

Motors rated in accordance with this specification must withstand without injury and without injurious sparking, the following *momentary excess torque*, after reaching the temperature corresponding to rated load :—

(a) *Continuous-rating motors*, including totally enclosed machines :—

50 % overload in torque for 1 min. for all sizes.

100 % overload in torque for 15 secs. for D.C. motors up to and including 150 B.H.P. per 1 000 r.p.m.

100 % overload in torque for 15 secs. for A.C. induction motors of all sizes [but excluding induction motors of 'abnormally low speeds or high frequencies and consequently of low power factor'; the overload capacity of such machines is a matter for special agreement].

(b) *Short-time rated motors*, including totally enclosed machines :—

100 % overload in torque for 30 secs. for all sizes.

Generators with continuous rating, including totally enclosed generators, must be capable of withstanding the following *momentary excess current*, after reaching the temperature corresponding to rated load—50 % overload in current for 1 min. for all sizes, the voltage being maintained as near the rated value as possible.

* For definitions see footnote, p. 7.

TABLE 110.—*Limits of Temperature Rise for Industrial Motors and Generators (when tested in accordance with B.S.S. No. 168—1926).*

Part of Machine.	Temperature Rise Measured by Thermometer (cooling air not above 40° C. ; for altitude correction, see § 1024).	
	Machines other than Totally Enclosed.	Totally Enclosed Machines.
	°C.	°C.
Windings with Class A. insulation,* and cores in contact with them . . .	40	50
Commutators	45	55
Slip rings :—		
Open type	45	55
Enclosed	55	55

Uninsulated parts, and cores not in contact with insulated windings.

Nowhere such that there is risk of injury to insulation on adjacent parts.

Motors and generators (other than 1-ph. motors) rated under this Specification shall be capable of carrying without injury the *sustained overloads* stated in Table 111, after reaching the temperature rise corresponding to their rated load, the voltage and frequency (if A.C.) being maintained at their rated values.

TABLE 111.—*Sustained Overloads for Industrial Electric Motors and Generators (B.S.S. No. 168—1926).*

Motors with Continuous Rating not Totally Enclosed.		Generators with Continuous Rating not Totally Enclosed.	
Size. H.P. per 1 000 r.p.m.	25 % Overload in Torque for	Size. kW (if D.C.), or kVA (if A.C.) per 1 000 r.p.m.	25 % Overload in Current at Full Rated Volts for
10 and over	2 hrs.	7½ and over	2 hrs.
Below 10, down to 4	½ hr.	Below 7½, down to 3	½ hr.
Below 4, down to 1	15 mins.	Below 3, down to 1	15 mins.

Machines with short-time rating and all totally enclosed machines are not capable of carrying sustained overloads.

The sustained overloads specified above are applicable only if the temperature of the cooling air does not exceed 35° C. (95° F.). If the cooling air is above 35° C. and

* For definitions see footnote, p. 7.

§ 6:

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it is desired to retain the full overload capacity, the continuous load must be correspondingly reduced below the rated load. On the other hand, if the cooling air is below 35° C, the duration of the overload on the smaller machines may be increased, but may never exceed 2 hrs.

Methods of measuring temperatures are described in § 1024, and high voltage tests for these machines are specified in § 1018.

Large Electric Generators and Motors: Rating Exceeding 2500 kw. (Maximum Sustained Output not greater than 24 kW, kVA or H.P. per r.p.m.). According to B.S.S. No. 163, 1925, the *rated load* of these machines is the load which can be carried for an unlimited period without exceeding the temperature rise specified in Table 112, Cols. I.

Motors rated in accordance with this Specification must withstand, without injury and without injurious sparking, the following *momentary excess torque* after reaching the temperature corresponding to rated load, the rated voltage and frequency (if A.C.) being maintained:

50 % overload in torque for 1 min.

100 % overload in torque for 15 sec., for A.C. induction motors (excepting those of 'abnormally low speeds or high frequencies and consequently of low power factor'; the overload capacity of such machines is a matter for special agreement.)

Generators must be capable of withstanding 50 % overload in current for 1 min. at as near the rated voltage as can be maintained.

Generators and motors rated under this Specification shall be capable of carrying without injury the following *sustained overloads*, after reaching the temperature rise corresponding to their rated load, the voltage and frequency (if A.C.) being maintained at their rated values:

Generators: 25 % overload in current for 2 hrs.

Motors: 25 % overload in torque for 2 hrs.

Methods of measuring temperature are described in § 1024; and high voltage tests for these machines are specified in § 1018.

Large Electric Generators and Motors: Continuous Maximum Rating (Rated output more than 2½ kw, kVA or H.P. per r.p.m.). According to B.S.S. No. 226, 1925, the *rated load* of these machines is the load which can be carried for an unlimited period without exceeding the temperature rise specified in Table 112, Cols. II.

This Specification does not permit machines to carry any sustained overload, but it demands that the following *momentary overloads* be carried without injury or injurious sparking, the voltage and frequency (if A.C.) being maintained at their rated values:—

Generators:—50 % overload in current for 15 secs.

Motors:—(a) *D.C. Motors*: 50 % overload in torque for 15 secs.

(b) *Synchronous Motors*: 50 % overload in torque for 15 secs., without dropping out of synchronism; the excitation being fully maintained.

(c) *Induction Motors*: 75 % overload in torque for 15 secs., without stalling (excepting motors of 'abnormally low speeds or high frequencies and consequently low power factor, and motors where a large excess torque is not required'; in such cases the value of the excess torque is a subject for special agreement).

Methods of making temperature measurements are described in § 1024; and high-voltage tests for these machines are specified in § 1018.

TABLE 112.—*Limits of Temperature Rise for Large Electric Generators and Motors (when tested in accordance with B.S.S. No. 169—1925 and 226—1925).*

I = Temperature rise permitted by B.S.S. No. 169—1925: RATING PERMITTING OVERLOADS.
 II = Temperature rise permitted by B.S.S. No. 226—1925: CONTINUOUS MAXIMUM RATING.

Item.	Part of Machine.	Temperature Rise (Cooling Air not above 40° C.; for Altitude Correction see § 1024).								Class B Insulation.*							
		Class A Insulation.*								By Resistance Method.				By Embedded Temperature Detector Method (Resistance Thermometer or Thermo-Couple). SEE NOTE (c).			
		By Thermo-meter Method. SEE NOTE (a).		By Resistance Method. SEE NOTE (b).						By Thermo-meter Method. SEE NOTE (a).		By Resistance Method. SEE NOTE (b).				Between Coils in one Slot.	
		I. (1).	II. (2).	I. (3).	II. (4).	I. (5).	II. (6).	I. (7).	II. (8).	I. (9).	II. (10).	I. (11).	II. (12).			Between Outside of Coil and Bottom of Slot.	
		°C.	°C.	°C.	°C.	°C.	°C.	°C.	°C.	°C.	°C.	°C.	°C.	°C.	°C.	°C.	°C.
1	A.C. windings of stators or rotors rated for not over 7 000 V.	40	55	45	60	50	65	65	80	65	80	65	80	55†	70†		
2	Doitto rated for over 7 000 V	¶	¶	‡	‡	¶	¶	‡	‡	65	80	‡	‡	¶	¶		
3	Field windings stationary or rotating (other than 4, 5, or 6).	‡	‡	50	60	‡	‡	80	80	‡	‡	‡	‡	‡	‡		
4	Exciter field windings.	40	55	‡	‡	50	65	‡	‡	‡	‡	‡	‡	‡	‡		
5	Low resistance field windings of more than one layer, or compensating windings.	45	60	‡	‡	55	70	‡	‡	‡	‡	‡	‡	‡	‡		
6	Single layer field windings with exposed surface.	50	65	50	65	65	85	65	85	‡	‡	‡	‡	‡	‡		
7	Short-circuited windings, insulated.	50	65	‡	‡	65	85	‡	‡	‡	‡	‡	‡	‡	‡		
8	Windings of armatures having commutators.	40	55	‡	‡	50	65	‡	‡	‡	‡	‡	‡	‡	‡		
9	Short-circuited windings, uninsulated.	Nowhere such that there is risk of injury to any insulating or other material on adjacent parts.															
10	Iron core and other parts not in contact with windings.																
11	Iron core and other parts in contact with windings.	Same as for adjacent parts, as given in Cols. 1 and 5 (or 2 and 6), or Cols. 3 and 7 (or 4 and 8) in the case of item 3, except that the correction specified in footnote ¶ shall not apply.															
12	Commutators.	(I) 45° C. (II) 55° C.															
	Slip rings: open.	(I) 45° C. (II) 55° C.															
	" " enclosed.	(I) 55° C. (II) 60° C.															

* For definition see footnote, p. 7.

† If desired by the manufacturer, in the case of stators wound with one coil side per slot, the temperature rise may be measured on the copper, inside the insulating tube; the permissible temperature rise is then (I) 70° C.; (II) 85° C.

‡ This method of measurement is not recognised in these cases.

¶ Reduce the values of temperature rise given for item 1 at the rate of 1½° C. for each 1 000 V or part thereof by which the voltage for which the windings are insulated exceeds 7 000 V. Windings for over 15 000 V are subject to special agreement.

NOTES.—(a) The thermometer method is applicable to those measurements of A.C. windings where neither the embedded temperature detector nor the resistance method is applicable. It is also the method to be used for the measurement of all series windings of low resistance, for exciter windings and miscellaneous parts (lines 9-12 in Table). Where thermometers are used as a check on the resistance method, their readings are subject only to the temperature limits of the resistance method.

(b) The method by increase of resistance of windings is applicable to all field windings (except stationary low-resistance field windings and exciter windings) and to stator windings of machines not requiring the use of embedded temperature detectors (Note (c)), except that it is not to be used for the A.C. windings of machines requiring more than 5 mins. to come to rest (the thermometer method is to be used in such cases). The resistance measurements shall be made before and during the temperature test.

(c) The embedded temperature detector method shall be used for the slot portion of stator windings in machines: (a) Having a rated output of 4 000 kVA, B.S.S. No. 169—1925 (5 000 kVA, B.S.S. No. 226—1925) or more. (b) Having an axial core length of 1 metre (3·28 ft.) or over.

The preceding paragraphs cover the definition of the horse-power of electric motors (and the kW or kVA of generators according to British standards. The choice of motor type and horse-power for specific applications is discussed in §§ 750 *et seq.* The I.E.E. Rules relating to motors and machine control gear are cited in § 781.

Duty-Cycle Ratings. Electric motors are often used to drive machines which operate on a short cycle of acceleration, more or less steady running, retardation and rest, this cycle being repeated periodically during a more or less prolonged period. Cranes, lifts and winding engines are familiar examples of such machines and there are many others in industrial service. The rating of motors for these conditions is a difficult problem and one which demands special consideration in each case. Obviously, the maximum or peak H.P. of the cycle bears no definite relation to the root-mean-square (R.M.S.) horse-power of the cycle. The motor must be capable of developing the maximum H.P. required without stalling and without injurious sparking; and it must not attain an injurious temperature at the end of the longest series of cycles required in practice. The root-mean-square H.P. of the cycle * is to some extent a measure of the heating to which the motor is subjected, but it must be remembered that the maximum temperature in each cycle is reached at the commencement of the idle period, and the extent to which the motor is hotter at the beginning of one cycle than it was at the beginning of the preceding one depends on the duration of the idle period and the actual temperature of the motor, the cooling facilities being constant. A short-period heavy load followed by a long period of idleness might give the same R.M.S. horse-power for the cycle as a lighter load maintained

* Calculated from the formula:—

$$\text{H.P.}_{\text{r.m.s.}} = \sqrt{[(A^2 t_1 + B^2 t_2 + C^2 t_3 + \dots) / T]},$$

where

$A = \text{H.P. required for } t_1 \text{ seconds,}$

$B = \text{ " " } t_2 \text{ "}$

$C = \text{ " " } t_3 \text{ "}$

etc., etc.

and $T = \text{total duration of cycle in seconds, including the idle period.}$

For example: If 20 H.P. is required for 5 secs., 40 H.P. for 15 secs., and the machine is idle for 40 secs., the R.M.S. horse-power

$$= \sqrt{[(400 \times 5) + (1600 \times 15)] / 60} = 21 \text{ H.P.}$$

approximately, but the motor would also have to carry 40 H.P. without injurious sparking.

during a greater part of the same total period, but the same motor would not be suitable for both services. The best course is undoubtedly to plot the actual heating curve (temperature against time) for the machine in the service concerned; the continuous or short-time rating of the motor is then P horse-power, where P is equal to that of the load which would bring it to the same final temperature in continuous or short-time (1 hr. or $\frac{1}{2}$ hr.) service as the case may be. Whether there is any point in determining the equivalent continuous or short-time rating in this way is another matter. It appears to the authors that the conditions of periodic intermittent loading are so varied that it is best to specify the exact requirements of the cycle and leave it to the designer and manufacturer to supply a machine capable of meeting them. In general, a motor for such service must be relatively more expensive in first cost and less efficient in operation than one driving a steady load. (See also § 752.)

Generally, a given motor is capable of carrying a heavier load in intermittent service than in continuous operation,* but, if starting is very frequent and the starting current very heavy, the machine may become hotter in intermittent service than it would on continuous full load. In such cases it is desirable either to use a motor developing higher starting torque per ampere or to start the driven machine through a clutch.

671. General Construction of Electric Motors.—The main components of any electric motor are the stationary field system or stator; the armature or rotor, with its shaft and bearings; and the commutator and / or slip rings, according to the type of machine concerned. The following notes indicate the principal features of modern motors; for further details reference may be made to treatises on motor design and to manufacturers' catalogues.

D.C. MOTORS.

Field System.—Yoke of cast iron or cast steel, split horizontally for convenience in the case of large machines. *Pole cores* fixed to the yoke by tap bolts, so that each core and its winding can be removed without disturbing others. The cores of the main poles may be of cast or forged steel with laminated pole shoes; or the

* The same size of motor carcass, costing approximately the same in both cases, will serve (for example) for the following outputs:—

Continuous rating.—1 B.H.P. at 1 350 r.p.m. or 2 B.H.P. at 2 250 r.p.m.

Short-time rating.—1 B.H.P. at 900 r.p.m. or 2 B.H.P. at 1 500 r.p.m.

whole core may be laminated. The cores of interpole (commutating pole) are sometimes laminated but generally solid, slot casting or forging. *Main field coils* are usually wound with double cotton covered wire and impregnated. *Series field coils* and *interpole windings* are generally of bare copper wound edge wise and insulated with full-board and empire cloth. *Compensating windings* (for neutralising armature reaction) consist of insulated bare or enamel coated slots in the pole shoes of the main field system.

Armature. The core consists of slotted laminations (complete rings in small machines; annular sectors in larger machines) dovetailed to a cast-iron 'spider' which is keyed to the shaft. Spacing pieces are built in between ventilating ducts and the laminations are clamped longitudinally by insulated bolts and end plates with projections bearing on the teeth of the laminations. *Former wound coils* are generally employed, with impregnated tape insulation, and tinned wrappings between turns and round the coils. *Slots* are lined with paraffin, leather, paper or similar material, and the coils are held in open slots by hard fibre wedges.

Commutator and Brushes. A cast-iron spider or nave keyed to the shaft carries hard-drawn copper bars insulated by mica-ite from each other, from the spider, and from the V-section end rings which hold the bars in place. The wearing depth of the copper should be not less than $\frac{3}{8}$ in. Carbon or graphite brushes, with flexible copper 'tails,' and independent adjustment of bearing pressure for each brush, are carried by brush holders mounted on brush spindles parallel to the shaft. The brush spindles are carried by, but insulated from, a ring known as the 'brush rocker,' which can be turned slightly in either direction in order to bring the brushes into the plane of sparkless commutation.

Terminal Marking.—At the time of writing (1933) the marking of terminals on D.C. machines is under consideration by the B.S.I. The Government Department Electrical Specification, No. 2 (Direct Current Motors), requires terminals to be marked as follows:—

Line terminals	L + and L -
Armature terminals	A and AA
Series field terminals	Y and YY
Shunt field terminals	Z and ZZ
Armature and shunt field	AZ

An earthing terminal must be fixed to the motor frame near the terminal box.

A.C. MOTORS.

Stator.—The frame usually consists of a box-type casting with cores holes for ventilation; it may be split for ease of transport but is almost invariably bolted permanently together in service. The core consists of laminations keyed or dovetailed to the yoke; semi-closed slots are usual, and the ventilating ducts and clamping are as in D.C. armatures (q.v.). According to the voltage of the machine and the maker's practice, coil or bar windings are used, with electrically welded connections between conductors.

Rotor.—In *salient-pole synchronous motors* the rotor consists of a D.C. field system substantially the same as that of D.C. motors (q.v.), except that the pole cores project radially outwards from the hub or spider and the whole system is designed to withstand rotation. In *induction motors*, *synchronous induction motors*, and *A.C. commutator motors*, the mechanical construction of the rotor is substantially the same as that of a D.C. armature (q.v.). In the squirrel-cage induction motor, bare copper bars are brazed to high-resistance end rings; in slip ring induction

motors, mica-wrapped copper bars, arranged as a phase winding, are connected to slip-rings; and in A.C. commutator motors the windings resemble more or less closely those of D.C. motors.

Slip Rings, Commutator and Brushes. Bronze slip-rings are standard, with carbon or metallised graphite brushes and, in some induction motors, automatic gear for short-circuiting the slip-rings and lifting the brushes to eliminate wear and resistance losses when the motor is running at full speed. Where a commutator is employed its construction is as in D.C. motors (q.v.).

Terminal Markings. B.S. Specifications Nos. 169 and 226 (1925) stipulate that 'for A.C. machines the letters A, B, C shall be adopted to indicate the external connections of a 3-phase machine, and the letter N shall be used to indicate a neutral connection.'

The reason for *laminating cores* is to prevent the circulation of heavy eddy currents induced in the iron by fluctuating or alternating magnetic fields. The laminations are thin sheets of high-permeability, low-hysteresis steel (§ 82, Vol. 1) of high electrical resistance, insulated on one side by paper or varnish, and, if the whole object of lamination is not to be defeated, there must be no burrs, bare clamps or other conductors short-circuiting the laminations. Short-circuiting by burrs may lead to welding together of the sheets and burning of insulation. Laminated cores must be clamped tightly to secure mechanical rigidity, and prevent humming due to vibration by magnetic forces.

The function of *interpoles* is to maintain sparkless commutation of the machines at all loads with a fixed brush position (*see also* § 139, Vol. 1). The same purpose is served in A.C. commutator motors by special *compensating windings*. In order to ensure satisfactory commutation in large variable-speed D.C. motors and in machines subject to abnormal overloads, compensating windings (sometimes called neutralising windings) are placed in slots in the main pole shoes, and connected in series with the armature in such polarity that they compensate for or neutralise the cross-magnetising effect of the armature, thus preventing the plane of commutation from being shifted by changes in the armature current (due to load) or in the main field current (for speed control).

The *polarity of interpoles in a motor* is opposite to that of the next main pole in the direction of rotation. Reversing the direction of rotation by *interchanging the terminals of the main field circuit* reverses the polarity of the main poles and, as the rotation is reversed, the polarity of the interpoles must remain as before; in other words, the interpole connections must *not* be interchanged in this case. On the other hand, if the polarity of

the main poles be left unaltered and the motor be reversed by reversing the polarity of the connections to the armature, the polarity of the interpoles must also be reversed. The former method of reversing the motor by interchanging the main field connections is simpler and is the one usually adopted. *Compensating windings* connected in series with the armature must also be reversed if the direction of current flow through the armature is reversed.

The ideal insulation between *commutator bars* is mica or mica-ite which always wears exactly flush with the copper. 'High mica' result when the insulation is so hard that it wears more slowly than the copper; the projecting mica wears the brushes rapidly and results in sparking. Undercutting the mica eliminates this trouble, but special care is needed to prevent carbon and copper dust from accumulation in the slots and short-circuiting the bars.

The *slip rings* of induction motors are sometimes mounted between the rotor and one of the bearings, especially in pedestal bearing machines, but placing the rings on a projection of the shaft beyond one bearing makes them more accessible, and reduces the deflection of the shaft by decreasing the distance between bearings. This is a consideration of special importance in induction motors, owing to the very short air-gap of these machines. The air-gap of salient-pole synchronous motors is much longer, and that of synchronous-induction motors is longer than the air-gap of an induction motor.

Up to about 100 H.P. the *bearings* of an electric motor can generally be carried by end-brackets or end-shields attached to the field or stator frame, but pedestal bearings are usual for larger machines and can be used in smaller motors if desired. Points which should not be overlooked are the possible advantages of vertical-shaft motors for some drives, e.g. centrifuges, some types of pumps, beaters, and so on; and the desirability of using a third bearing, outside the pulley, when driving very heavy loads by belt, rope, or chain. Ball and roller bearings are being used to an increasing extent for electric motors; they save space, reduce friction and, when properly packed, run satisfactorily in the dirtiest surroundings with a minimum of attention. The negligible wear of ball and roller bearings is a valuable feature where induction motors or other machines with very short air-gaps are concerned.

Standard types of enclosure for electric motors are defined in § 670. Protected, enclosed ventilated, and enclosed motors with or without pipe ventilation are the most generally useful types in industrial service. Total enclosure materially reduces the natural cooling facilities of a motor and hence reduces its rating (§ 670). Cooling may be facilitated by casting radiator-gills on the motor casing; by providing inlet and outlet openings in the casing and pumping clean air through the latter; or, for use in explosive atmospheres, by arranging fans on the motor-shaft to draw air through ventilating ducts in the carcass of the machine, these ducts being so arranged that they do not communicate with the enclosed portion of the casing wherein the windings are situated and within which all sparking is confined. This method of cooling results in the rating of the motor being from 80 to 100 % of that of an open-type motor using the same frame.

The amount of heat which can be dissipated by a totally enclosed motor without exceeding the permissible temperature-rise is strictly limited, but can be increased by increasing the radiating surface, e.g. by forming fins or corrugations on the outside of the frame and end covers. Increasing the motor speed does not increase the natural cooling of the enclosed machine, but it does increase the core losses, hence, as the speed is increased, a limiting H.P. is reached beyond which it is not safe to go with a particular frame. The H.P. of a well-ventilated motor increases roughly with the cube of the dimensions, but the cooling surface of the frame increases only with the square of the dimensions, hence heating becomes a more serious problem in enclosed motors as the size of the latter increases. There is no difficulty in running small motors totally enclosed, but larger machines become relatively very heavy for the output which they can develop when totally enclosed, and the advantages of forced ventilation become proportionately greater.

Theoretically, a totally enclosed motor is immune from dust and dirt in the surrounding atmosphere. This is true only if the machine be thermetically enclosed. Otherwise, changes in temperature cause a "breathing" action (cf. § 598, Vol. 2), air being expelled from and drawn into the casing through interstices as the motor heats up and cools down. In this way a certain amount of dust is drawn into the machine and accumulates there. Forced ventilation of an enclosed machine by clean air not only increases its rating by cooling it more effectively but also keeps the windings clean. As the dangerous phase of the "breathing" action is when the motor cools down, the connection to the clean air supply must remain open during this period, otherwise dust-laden air will be drawn in through interstices as before.

Special air filters have been designed for use with open-type motors which are to be installed in dusty situations. The air passes through the interstices of a stack of closed spaced metal plates, the latter having been dipped in an oil which forms a viscous, dust-retaining film on the metal. The filter must be washed periodically in paraffin, petrol or soda water, after which it is re-dipped in the dust-retaining oil and allowed to drain before it is returned to the motor. It is for the user to decide whether the smaller size and lower cost of the ventilated motor, compared with the total enclosed machine of equal rating, justifies the trouble of attending periodically

to the filters. If the latter be neglected they may become either dirty or clogged, with the result that dust gains access to the motor and the machine is liable to overheating owing to the ventilation being throttled. Whenever such a motor is installed, an air outlet should be connected to a pipe leading to a dust-free place, otherwise dust will enter the machine when it is standing still.

During recent years there has been considerable discussion concerning the *cooling of electrical machinery by hydrogen*. The specific heat of hydrogen is much higher than that of air, about 3·4 as compared with 0·24, hence 1 lb. of hydrogen carries off $3·4 / 0·24$ or about 14 times as much heat as 1 lb. of air for the same temperature-rise. Also, hydrogen will not support combustion and will therefore not assist the burning of insulation in the event of arcing. On the other hand, a machine which is cooled by hydrogen must be totally enclosed by a gastight, explosion proof casing, for a mixture of hydrogen and air is highly explosive. A hydrogen-cooled synchronous condenser (*i.e.* an over-excited synchronous motor used solely for P.F. correction, § 160, Vol. 1) installed on the New England Power Company's system at Pawtucket, R.I., is rated at 12 500 kVA; if air-cooled its capacity would be 10 000 kVA.

The *reliability* of electric motors is extraordinarily high and, provided that the conditions of service are specified when the machine is ordered, and that the motor is properly installed with the usual protective features (§ 743), it is proof against almost every contingency—to a far greater extent, in most instances, than the machine which it drives.

In steel works, motors of from 1 to 150 H.P. run about 6 500 hours per annum (compared with, say, 8 000 hours per annum in other industries) driving auxiliary equipment of all descriptions under conditions of mechanical shock, heat and dirt which are probably more severe than those in any other service. Yet, according to records covering a long period (*Gen. El. Rev.*, Vol. 31, p. 305) the armature coils of modern mill-type motors last 7 to 8 years, bearings over 10 years, and commutators over 20 years. In easier service longer life could be obtained from these motors or, alternatively, a lighter construction could be employed for equal life.

The *cost* of a motor depends largely on the speed at which it is designed to work; for a given B.H.P. of output the size of the motor carcass decreases as the armature speed increases. In the case of D.C. motors the range of speed obtainable is very great, as will be seen from the tables in later paragraphs; with synchronous and induction motors the limits of speed are much less elastic, as the revolutions per minute depend to a greater or less extent on the supply frequency or number of cycles per second.

672. Characteristic Curves of Motors.—The capabilities of any electric motor may be conveniently represented by a set of 'characteristic curves' which usually show the torque, current consumption, speed, efficiency and power factor (A.C. only) of the machine at various outputs, the latter being expressed in B.H.P. Sometimes the curves are plotted to a base line of current consumption (this is usual where traction motors are concerned) or to a scale showing the fractions of full-load output; in either of these cases a curve showing the B.H.P. output should be added. Where traction motors are concerned a curve of tractive effort is often substituted for the torque curve, thus taking account of the gearing, if any, between the motor and the driving wheels.

Characteristic curves for all the principal types of electric

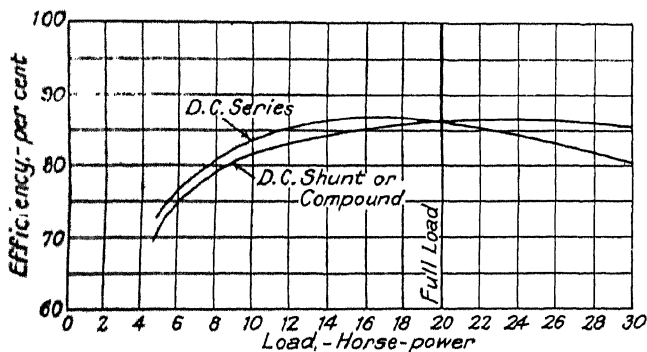


FIG. 249.—Typical efficiency curves for D.C. motors rated at 20 H.P., 1000 r.p.m. (see also Fig. 246).

motors are given in the paragraphs respectively devoted to each. Exceptionally interesting and instructive comparisons are to be obtained, however, from the sets of curves in Figs. 246-251 and in Figs. 252-253 respectively. The curves in 246-251 are replotted from sheets kindly prepared by the General Electric Co., Ltd. (Witton), specially for this book. These curves relate to the principal types of D.C. and A.C. motors built by the G.E.C., and all refer to machines rated at 20 H.P., 1 000 r.p.m. (approx.), to facilitate comparisons. It should be noted, however, that the precise form of the characteristic curves can be modified to meet particular requirements and, in each case, the efficiency and power factor curves do not necessarily represent the best results attainable but are given for general guidance.

Table 113 summarises the characteristics shown in Figs. 246, 251. The efficiency of larger motors is higher and that of smaller

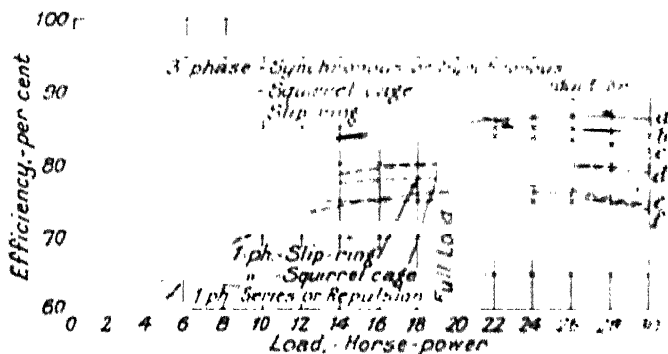


FIG. 250. Typical efficiency curves for A.C. motors rated at 20 H.P., 1000 r.p.m. (approx.) (see also Figs. 247, 248).

machines lower than the values shown in these Figs. and Table. For example, the average efficiencies and power factors of 114

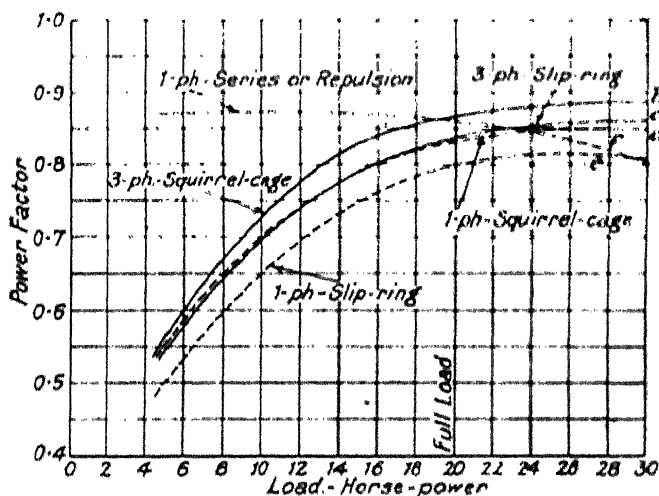


FIG. 251. Typical power factor curves for A.C. motors rated at 20 H.P., 1000 r.p.m. (approx.) (see also Figs. 247, 248).

and A.C. motors of various makes and outputs are approximately as stated in Table 114.

armature increases with load (§ 669). In such cases *differential* compounding (§ 677) is necessary if constant speed is to be maintained at all loads.* In large motors, however, the increased armature reaction at heavy loads may weaken the shunt field to such an extent that the motor speed has to *increase*, even to generate the lower back-E.M.F. required to permit the flow of the heavier armature current; a certain amount of *cumulative*

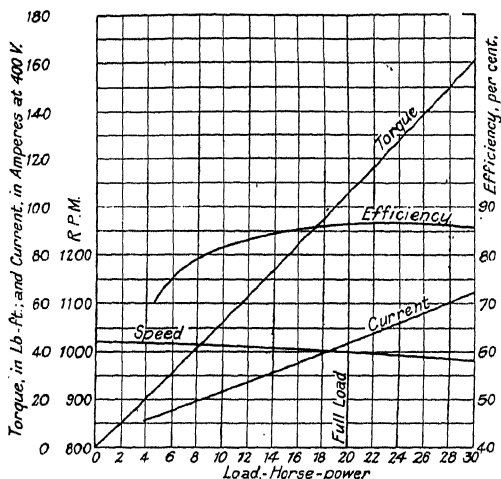


Fig. 257.—Typical characteristics of D.C. shunt motor. Rated output 20 H.P., 1 000 r.p.m. (see also Figs. 246, 249).

compounding (§ 677) is then needed to maintain constant speed at all loads.

The speed of any shunt (or compound) wound D.C. motor tends to increase appreciably as the machine 'heats up' in service. This is due to the decrease in shunt field current as the resistance of the field windings increases with their temperature (§ 61, Vol. 1). In

* An alternative method, applicable only to non-reversing interpole motors, is to displace the brushes backwards, against the direction of rotation of the armature. This causes a belt of armature conductors (occupying twice the angle of brush displacement on each side of the armature in a 2-pole machine) to exert a directly demagnetising effect on the main field. The demagnetising effect increases with the load on the machine and, by selecting the appropriate brush displacement, it can be arranged that the speed of the motor is practically constant at all loads, the demagnetising effect of the armature compensating for the decrease in speed otherwise produced by the increase in armature IR drop.

some applications, as, for example, the driving of textile machinery, special attention must be paid to the changes in the speed caused by temperature variations. The speed can, of course, be adjusted periodically by means of a field rheostat and this adjustment can hardly be avoided in the case of a variable speed shunt motor which, at its higher speeds (weaker fields) is necessarily working on the steep part of its magnetisation curve (§ 81, Vol. 1), so that a small change in field current produces a considerable variation in field strength and armature speed. In the case of constant speed machines, however, the field system may be worked near magnetic saturation, *i.e.* beyond the 'knee' of the magnetisation curve (Fig. 12, § 81, Vol. 1); a small change in field current, such as that caused by heating of the windings, then results in no appreciable variation of speed.

Though the speed of the shunt-wound D.C. motor is practically independent of load as long as the field strength is constant, it can be varied over a range of 6:1 by the changing strength of the field current. Such a wide range of control is only needed in special cases and, if required, it must be specified when the motor is ordered, so that the machine may be designed to permit the requisite variation of field (*see also* § 717). Halving the field flux halves the torque developed per ampere of armature current, but, the armature ω being doubled, the H.P. (proportional to torque \times speed) remains constant; in other words, the shunt motor develops constant H.P. for given armature current as long as the speed is controlled by variation of field.

For any particular load the armature loss is practically the same at all speeds. Friction loss increases in proportion to the speed, and windage with the square of the speed. Eddy current and hysteresis losses in the iron are higher at higher speeds, but the loss in the field windings decreases as the speed is raised by decreasing the field current. On the whole, the losses are greater at the higher speed, so that the efficiency of a variable speed D.C. shunt motor may be 2 or 3 per cent. lower on full-load at maximum speed than on full-load at minimum speed; and the difference greater at fractional loads (*see* Fig. 258).

Motors of unduly low or extra high speed are alike more costly than those of medium speed, the low-speed motors being dear because of their extra size and weight, and the high-speed machines because of the mechanical construction required to withstand high-

speed rotation. Typical ranges of horse-power and speed for industrial D.C. shunt motors are given in Table 115. For special

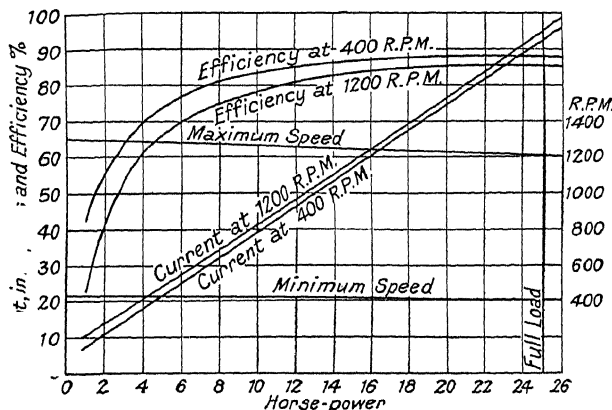


FIG. 258.—Typical speed and efficiency curves of 25 H.P., 230 V D.C. shunt motor at different speeds (obtained by field control).

applications, such as centrifugal pumps, fans and similar machines, shunt motors can be built for speeds up to 3 000 or even 5 000 r.p.m. in medium and large sizes.

The direction of rotation of a shunt-wound D.C. motor may be reversed by reversing either the armature current or the field current (*not* both). The simplest method is to interchange the terminal connections of the shunt field circuit; also the series turns on the main poles where these are provided for steadying purposes in shunt motors of wide speed range. If the connections to the armature (*i.e.* to the brushes) be reversed, the terminal connections of the interpoles (if any) must also be reversed.

Shunt motors should not be coupled mechanically in parallel because a very slight difference between their inherently flat speed-load curves

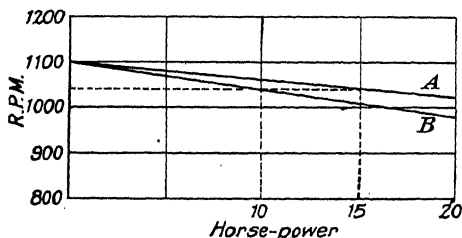


FIG. 259.—Unequal division of load between D.C. shunt-wound motors coupled mechanically.

results in a serious inequality between the loads on the two machines. Thus, in Fig. 259, machines A and B when running

TABLE 115. *Approximate Data for D.C. Shunt Wound Motors*

These particulars are based on typical standard machines by the General Electric Co., Ltd., London. The speeds given correspond to standard voltages, 220 and 440 V, but a machine wound for 220 V may be supplied at 240-240 V (and a 440 V motor at 430-480 V) with only a slight variation in temperature rise. The B.H.P. output varies in direct proportion to the variation of voltage from standard; and the speed varies approximately in proportion to the voltage for voltages above standard, and 0.5% for each 1% voltage variation below standard. The speeds stated are the mean speeds at full load, after reaching the final temperature of the machine. Generally, 25% increase in speed can be obtained in shunt motors up to 5 H.P. (50% increase in larger machines), by use of a shunt field regulator. In some cases, as shown by the Table, the maximum speed is obtainable from a particular frame size imposes a lower range of speed variation. If a larger range of speed is required (up to 2 or 3 times normal full load speed), compound wound motors should be used; yet wider variation of speed can be obtained if specially required. For pipe-ventilated motors, increase the speeds stated for protected and enclosed ventilated motors by 5%, and reduce the output by 10% for machines tabulated up to 15 H.P. inclusive, and by 5% for 20 and 30 H.P. machines. Above 30 H.P., the outputs are as stated for pipe-ventilated motors, but the speeds are 5% higher than for protected and enclosed ventilated machines.

Horse-Power.	Protected and Screen-Protected (Enclosed Ventilating) Types.					Totally Enclosed Type				
	Revs. per Minute.		Max. by Shunt Field Regulator.	Efficiency, %	Net Weight of Motor and P. in Approx. Lb.	Revs. per Minute		Max. by Shunt Field Regulator.	Efficiency, %	Weight of Motor and P. in Approx. Lb.
	220 V.	440 V.				220 V.	440 V.			
½	750	800	1 000	64	144	1 000	1 000	1 250	71	144
	500	550	687	62	180	720	720	900	68	180
1	1 000	1 000	1 250	69	144	1 050	1 180	1 437	75	180
	720	720	900	68	180	720	720	900	75	804
	480	480	600	65	304	520	550	687	73	814
3	1 550	1 550	1 987	80	180	1 200	1 200	1 500	79	814
	1 000	1 000	1 250	80	304	1 000	1 000	1 250	80	616
	700	700	875	80	814	780	780	975	80	764
	580	580	658	78½	816	—	—	—	—	—
	450	450	562	72	764	425	425	531	79	1 077
	300	300	375	72	812	—	—	—	—	—
5	1 500	1 500	1 800	84	304	1 200	1 200	1 400	84	764
	1 000	1 000	1 250	84	314	875	875	1 094	83	812
	770	770	962	79	616	730	730	912	83	1 077
	520	520	650	77	764	525	525	656	83	1 300
	440	440	550	77	812	—	—	—	—	—
	340	340	425	76½	1 077	350	350	437	83	1 624
	270	270	337	76	1 400	—	—	—	—	—

TABLE 115 (cont.)-

Horse-Power.	Protected and Screen-Protected (Enclosed Ventilated) Types.					Totally Enclosed Type.							
	Revs. per Minute.			Efficiency. %.	Net Weight of Motor and Pulley (Approx.). Lb.	Revs. per Minute.			Efficiency. %.	Net Weight of Motor and Pulley (Approx.). Lb.			
	220 V.	440 V.	Max. by Shunt Field Regulator.			220 V.	440 V.	Max. by Shunt Field Regulator.					
7½	1 500	1 500	1 600	87½	314	7 H.P.	1 250	1 250	1 250	84	812		
	1 000	1 000	1 500	81	616		—	—	—	—	—		
	700	700	1 050	80	764		—	—	—	—	—		
	550	550	825	79	812		—	—	—	—	—		
	450	450	675	78½	1 077		480	480	600	84	1 624		
	270	270	405	78½	1 624		—	—	—	—	—		
	200	220	330	75	2 240		—	—	—	—	—		
	10	1 350	1 350	1 500	83		616	10 H.P.	1 100	1 100	1 200	86	1 400
540		540	810	81½	1 077	720	720		1 080	87	1 624		
440		440	660	81	1 400	510	510		765	86	2 240		
250		250	375	77½	2 240	400	400		600	86	3 024		
190		190	285	76	3 920	—	—		—	—	—		
15		1 500	1 500	1 500	85½	764	15 H.P.		—	—	—	—	—
		1 200	1 200	1 200	85	812			—	—	—	—	—
		820	820	1 230	85	1 077			850	850	1 100	88½	2 240
	630	630	945	84	1 400	—		—	—	—	—		
	425	425	637	84½	1 624	—		—	—	—	—		
	290	290	345	80½	3 920	—		—	—	—	—		
	165	165	247	78	4 592	—		—	—	—	—		
	20	—	990	1 250	86	1 077		20 H.P.	—	—	—	—	—
800		800	1 200	86	1 400	—	—		—	—	—		
540		540	810	85½	1 624	600	600		900	89	3 024		
470		470	705	83½	2 240	—	—		—	—	—		
280		280	420	82½	3 920	370	370		555	89	4 592		
200		200	300	82	4 592	—	—		—	—	—		
170		170	255	80½	5 824	—	—		—	—	—		
30		725	725	1 087	87½	1 624	30 H.P.		—	—	—	—	—
	500	500	750	86½	3 024	550		550	825	91	4 592		
	350	350	525	84½	3 920	420		420	630	90	5 824		
	275	275	412	84½	4 592	—		—	—	—	—		
	170	185	277	83½	6 720	—		—	—	—	—		
	40	1 000	1 000	1 100	83	1 400		40 H.P.	800	800	900	87	1 624
		700	700	800	81	1 624			600	600	700	86	2 240
		500	500	600	79	2 240			400	400	500	86	3 024
350		350	420	77	3 024	300	300		400	86	3 920		
250		250	300	75	3 920	200	200		300	86	4 824		
175		175	210	73	4 824	150	150		210	86	5 824		
125		125	150	71	5 824	100	100		150	86	6 720		
75		75	90	69	6 720	50	50		75	86	7 620		

TABLE 115 *cont.*

Horse-Power.	Protected and Screen Protected (Enclosed Ventilated) Types.					Totally Enclosed Type.				
	Revs. per Minute.					Revs. per Minute.				
	220 V.	110 V.	550 V.	440 V.	330 V.	220 V.	110 V.	550 V.	440 V.	330 V.
40	960		1 200	89	1 624					
	770		1 100	88	2 240					
		600	900	88	3 024					
	480	480	720	87½	3 920					
	340	340	510	86½	4 592					
	275	300	450	86	5 824					
50	340	230	345	86	6 720					
	670	760	1 050	89	3 024	950	950	1 500	92	4 592
	420	420	630	88½	4 592	400	700	700	92	5 824
							400	500	92	7 200
	750	750	950	90½	3 920					
	470	470	705	90½	4 592					
75	360		540	89	6 720					
100		1 000	1 000	91	3 920					
		570	780	92	5 824					
	500	500	750	92	6 720					
170		750	750	93½	6 720					

at the same speed, as is necessarily the case if they are mechanically coupled, carry loads of 15 H.P. and 10 H.P. respectively (cf. Fig. 262).

Summary of Characteristics and Applications. The D.C. shunt-wound motor is inherently a constant speed machine. Its speed can, however, be varied by varying the strength of the field or the voltage applied to the armature. The H.P. of the motor varies with the product: Field strength \times Armature current \times r.p.m. For any particular value of armature current: (1) the torque is constant and the H.P. varies with the speed, if the latter be varied

by altering the voltage applied to the armature, the field strength being kept constant by separate excitation; (2) the torque varies inversely with the speed and the H.P. is constant, when the speed is varied by altering the field, and the voltage applied to the armature is constant. About 25 % variation in speed can be obtained by field control in an ordinary shunt motor not designed specially for speed variation; and up to 5 or 6 : 1 speed range can be obtained by field variation if commutating poles are used and the field system is designed to suit the wide range of field current then required.

Shunt-wound motors are particularly suitable for loads such as lineshafts, lathes, milling machines, conveyors, fans, etc., which have to be driven at constant speed regardless of the load until such time as the speed is changed deliberately to a different setting. A shunt motor which normally drives a belt or chain conveyor can be used to limit the speed by regenerative braking when a descending load drives the conveyor.

Shunt-wound motors are not inherently suitable for use with flywheels; and they should not be used for very fluctuating loads because, in attempting to maintain constant speed, they take a heavy current during the periods of peak load. Where abnormally heavy torque may be required, series- or compound-wound motors are to be preferred if a decrease in speed with increasing load is permissible.

The starting and control of shunt motors are discussed in § 717.

676. Series-Wound D.C. Motors.—As implied by the name of the machine, the field winding of a series-wound motor is connected in series with the armature and carries the same current as the latter unless part of the current is diverted through a resistance in parallel with the field winding for the purpose of speed control (§ 718). The field winding consists of relatively few turns of heavy wire, and the field current is equal or proportional to the armature current, as the case may be. The excitation of the machine therefore increases with the load and reduces the speed of the machine; conversely, the speed rises as the load decreases and becomes dangerously high on no-load because the armature current is then very small (necessitating a back-E.M.F. practically equal to the supply voltage) and the field is very weak, so that a very high speed is needed to generate the requisite back-E.M.F. For this reason a D.C. series motor should never be used where the load

may become light or where it may be 'lost' by the breakage of a driving belt or otherwise.

At the moment of starting, a heavy current flows through the armature and field windings of a D.C. series motor, limited only by the value of the starting resistance plus the usually very low resistance of the windings themselves.* The heavy armature current, together with the heavy excitation of the field, results in a very powerful starting torque. As the speed rises the torque falls (see Fig. 260) but it is evident that a dangerously high speed

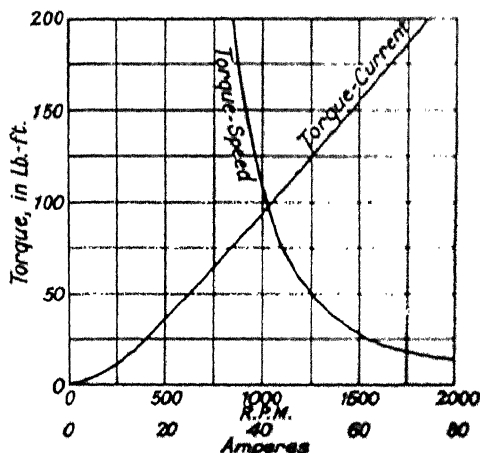


FIG. 260.—Typical torque-speed and torque-current curves for D.C. series-wound motor.

will be reached before the torque falls to that required to run the motor on no-load. Running on light load may be prevented by a pair of short-circuited brushes on an axis perpendicular to that of the main brushes; the effect is to produce a field aiding that of the field winding and increasing with the armature speed so that the necessary back-E.M.F. is generated without excessive rise of speed.

If the field strength were always proportional to the field current, *i.e.* if there were no magnetic saturation, the torque would vary with the square of the armature current and approximately inversely with the square of the armature speed; the speed would then vary nearly inversely with the current. **Actually**, the field strength tends to become constant as the current increases, owing to magnetic saturation, hence the torque approaches direct proportionality to the current on heavy loads. **At medium loads the**

* Small series-wound fan motors have a relatively high resistance and can be switched straight on to the supply.

torque increases less rapidly than the square of the current, and the speed decreases less rapidly than the inverse of the current.

As complete saturation of the field system is approached, the characteristics of the machine resemble those of a shunt-wound motor, i.e. the speed tends to become constant but at a very much lower value than the speed on medium load.

Typical characteristic curves for a D.C. series motor rated at 20 H.P., 1 000 r.p.m., are given in Fig. 261 to a base of horse-power.

The characteristic curves of series traction motors are commonly plotted to a base of current values (see Fig 338, § 718).

Reversal of a series-wound motor is effected by interchanging either the armature leads or the field leads, so as to reverse the direction of current flow through either the armature or the field, but not both.

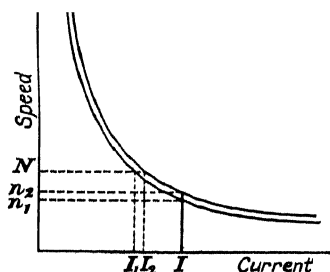


Fig. 262.—Illustrating operation of D.C. series motors in parallel.

between the currents I_1 , I_2 if the machines are compelled to run at the same speed by mechanical connection; or, alternatively, if

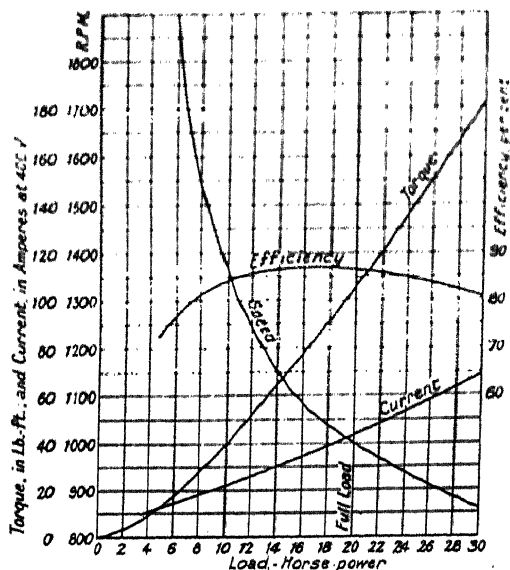


Fig. 261.—Typical characteristics of a D.C. series-wound motor. Rated output 20 H.P., 1 000 r.p.m. (see also Figs. 246, 249).

the motors are mechanically free to run at different speeds the actual difference between n_1 and n_2 is small for the same current in each machine (cf. Fig. 253b).

Summary of Characteristics and Applications. The D.C. series-wound motor is a varying speed machine. It develops high starting torque, and the speed varies inversely with the load. This motor is therefore particularly suitable for traction and haulage purposes, for cranes and other hoisting service, and for such purposes as moving heavy slides, or cross rails in machine tools, etc. Stable adjustment of speed (speed-setting) is impossible where the load is variable, and the series-wound machine must never be used where the load can be removed or reduced to a low value, unless an automatic device is used to limit the speed of the machine or open the circuit when a predetermined speed is attained. The automatic variation of speed with load enables advantage to be taken of fly-wheel storage, but, on the other hand, the presence of the flywheel tends to reduce the speed variations. Where, as is usually the case, the motor has to be frequently started and stopped, a flywheel should not be used; it would increase the current taken during acceleration and the energy stored in the flywheel would have to be dissipated at each stop. Small fans are often driven by series motors, the rapid increase in power absorbed as the speed increases (§ 764) preventing any dangerous racing; it is only on a load of this type that the D.C. series motor can safely be started 'light.' A series motor should not be used with a belt drive or to drive a conveyor belt or chain because breakage of the belt or chain would permit the motor to race. As long as the magnetic circuit is unsaturated the H.P. of the series motor varies nearly inversely with the speed, and the torque varies nearly with $1/(\text{speed})^2$.

The starting and control of series motors are discussed in § 718.

677. Compound-Wound D.C. Motors. The field magnets of a compound-wound motor are excited by two windings, one a shunt winding, *i.e.* a high-resistance winding of many turns connected in parallel with the terminals of the machine, the other a series winding, *i.e.* a low-resistance winding of few turns connected in series with the armature. According to the ratio between the ampere-turns of the shunt and series field windings, and according to whether the series winding assists the shunt winding (*cumulative compounding*) or opposes the shunt winding (*differential compounding*) the characteristics of the compound motor vary

over a wide range. Usually, the series field winding assists the shunt winding, and the term 'compound motor,' without qualification, generally means a cumulatively compounded machine. The ampere-turns of the cumulative series winding are generally between 10 and 30 % of the shunt ampere-turns* and their purpose is to increase the starting torque of the motor, and (unless the series turns are short-circuited when the machine is up to speed) to increase the momentary overload capacity of the motor and give it a drooping speed characteristic. The latter makes possible the use of a fly-

wheel. Temporary compounding, by series coils which assist the shunt field coils during starting and are then short-circuited, augments the starting torque and leaves the machine a plain shunt-wound motor as regards its performance during normal running. The purpose of differential compounding is to keep the motor speed constant at all loads

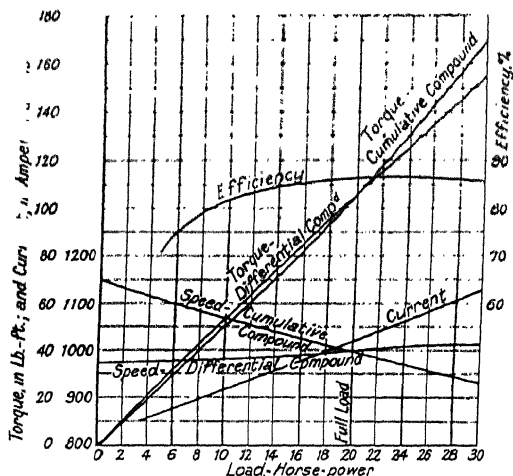


FIG. 263.—Typical characteristics of D.C. compound-wound motors. Rated output 20 H.P., 1000 r.p.m. (see also Figs. 246, 249).

or even to cause it to rise with increasing load. The overload capacity of the machine is then reduced, the motor becomes definitely unsuitable for use with a flywheel, and certain difficulties are introduced in the starting of the machine as noted below. Typical characteristic curves for compound motors with cumulative and differential compounding are given in Fig. 263.

* If desired, the proportion of series field may be only that required to prevent the increase in speed which might otherwise occur in a large shunt motor due to armature reaction on heavy load; or the proportion of series field may be so high that the machine is essentially a series motor safeguarded against racing by the shunt field.

Accidental reversal of polarity of the series coils in a motor *intended to be cumulatively compounded* will make the machine differentially compounded. According to the relative strength of the series and shunt excitation, the speed of the machine will rise with increasing load to a greater extent the stronger the series excitation. With a powerful series field of incorrect polarity, the motor may fail to start (the starting torque required is often high where a heavily compounded motor is selected) or it may start and run temporarily in the wrong direction. Even when the motor starts and runs satisfactorily on light load, the reverse series excitation will probably cause sudden acceleration and severe sparking when the load is applied.

Transient phenomena due to transformer action between the series and shunt field windings of D.C. *cumulatively-compound* motors sometimes affect the starting performance of the machine quite appreciably. The rush of current through the series field coils at the moment of starting induces a back E.M.F. in the shunt field coils on the same poles and, owing to the rapid change of flux and the relatively high number of turns in the shunt coils, the induced back-E.M.F. is usually higher than the applied forward-E.M.F. A reverse current therefore flows temporarily in the shunt field circuit, with the result that the shunt field opposes the series field and the starting torque is less than it would be with the series coils alone in action. Within a short time, usually $\frac{1}{4}$ sec. or less, from the start, the shunt field current commences to flow in the proper direction, the shunt turns then assisting the series turns but at the actual moment of switching on the motor the starting torque may be only 50 % of what it would be in the absence of the shunt coils. Owing to the transient nature of the differential action, the phenomenon is only of practical importance when the motor has to be started very frequently and it is desired to realise the highest possible starting torque, but the fact that the action occurs should be borne in mind.*

The transient action in a *differentially-compound* motor is of greater practical importance. In this case, the series field opposes the shunt field and, as the former builds up more rapidly, the motor may start in the reverse direction. The inductive action between

* Experimental data and methods for reducing the effect of this transient action are given by L. R. Ludwig, *Jour. Amer. I.E.E.*, Vol. 47, p. 258.

the series and shunt field windings tends to reduce the negative starting torque, but the latter exists until the shunt field has overcome that due to the series field coils.

Indirectly (Cumulatively) Compounded Motors. If a shunt motor is compounded in order to obtain a level or very slightly drooping speed-load characteristic and is, at the same time, to be used as an adjustable-speed motor, provision must be made for varying the amount of series excitation to suit the shunt excitation in use at any moment. This may be done by 'diverter' control, *i.e.* by switching suitable resistances in or out of parallel with the series field winding, but a more accurate and flexible method consists in separately exciting the series field from a 'series exciter.' The latter is an auxiliary generator excited by the armature current of the compound motor. A variable rheostat in series with the exciter adjusts the series excitation of the main motor and, by coupling the shunt field rheostat mechanically to the rheostat in the series field circuit, the two fields are adjusted automatically to maintain proper compounding at each setting of the speed. This system is used extensively to secure close speed regulation in D.C. motors driving tandem rolling mills,* and Table 116 shows the almost constant speed thus obtained from no-load to double-load in the case of a 2 500 H.P., 160 / 320 r.p.m., 600 V motor.

Summary of Characteristics and Applications.—The characteristics of the *cumulatively-compounded* motor are intermediate between those of the shunt and series motor both as regards starting torque and as regards speed-drop on load. The motor does not race on light load. Its speed-drop on increasing load increases with the proportion of the excitation provided by the series field winding; the variation of speed with load is easily made sufficient to enable a flywheel to be used to advantage. Generally, the speed variation of this type of motor does not exceed 20 %. The speed at any particular load can be regulated by means of a rheostat in the shunt field circuit; and, by cutting out the series field winding, the motor becomes a plain shunt-wound machine. When used with a flywheel, the cumulatively-compounded motor is suitable for driving planers, punches, shears, guillotines and other heavy machines subjected to intermittent peak loads. It is also suitable

* See 'The Drive of Tandem Rolling Mills,' A. F. Kenyon, *Jour. Amer. I.E.E.* Vol. 47, p. 445.

TABLE 116. *Speed Regulation of Indirectly Compounded D.C. Motor*

Shunt Field Current, Amperes	Load	Armature Current, Amps.	Motor Speed, R.P.M.
35.8	Light	100	160
	Full	3.000	160
	Double	6.750	159
19.2	Light		210
	Full	3.000	210
	Double	6.750	210
11.0	Light	100	265
	Full	3.000	265
	Double	6.750	264
10.8	Light	100	320
	Full	3.000	320
	Double	6.750	319

for driving rolling mills, hoists, winding engines, etc., with or without supplementary flywheel effect. For rolling mill and similar services, cumulative compound-wound motors are made in sizes up to 20 000 H.P. or over, for voltages up to 2 000 to 3 000 V. D.C. compound motors are sometimes used to drive conveyors; their high starting torque is a valuable feature, but if the conveyor is sometimes driven by a descending load there is a risk of racing, due to the reversal of the series field weakening the resultant field of the machine.

In the *differentially-compounded* motor, the function of the series field winding is to reduce the resultant excitation of the motor as the load increases and thus compensate for the decrease of speed which would occur in a motor excited by a shunt field winding alone. This type of motor is used where constant speed is required over a wide range of loads. The opposing series turns when carrying the starting current naturally reduce the starting torque to a value much below that which would be produced by the shunt field alone. In some instances, the series field builds up so much more rapidly than the shunt field that the motor starts in the reverse direction, and is then stopped and re-started in the proper

direction as the shunt field comes into action; if this occurs, there is severe mechanical shock and a heavy rush of current at the moment of reversal. Starting in the correct direction and with high torque may be secured by temporarily reversing the series field winding, so that the machine starts and accelerates as a cumulatively-compounded motor.

A compound motor may be reversed by reversing the direction of current flow through the armature and interpoles, if any, but *not* through the series field coils. If reversal be effected by reversing the shunt field coils, the series field coils must also be reversed, to maintain the correct relation between the shunt and series fields.

The starting and control of compound motors are discussed in § 720.

678. Constant-Current D.C. Motors.—Though the constant-current D.C. system of electricity supply involves considerable difficulties where very high voltages are used for the long-distance transmission of energy (§ 317, Vol. 1), it offers important advantages at low and medium voltages where a number of motors close together have to be operated at widely varying loads and speeds, as in the case of cargo-handling and other auxiliaries on shipboard. For such purposes, a constant-current equipment has been developed by Gilbert Austin, Ltd. A special constant-current dynamo is required. This is driven by an ordinary motor supplied from constant-voltage mains, and it maintains a constant current in a permanently closed series circuit through all the motors in service. A motor is switched 'off' by short-circuiting it, the constant current still continuing to flow through the distributing cable and any other motors which are still working. When all the motors are 'off,' the dynamo is short-circuited through the cable alone, and its E.M.F. is automatically reduced to the low value required to maintain the constant current under these conditions. As each motor is switched 'on,' by opening the short-circuiting switch across its terminals, the dynamo voltage is automatically increased by the amount of the back-E.M.F. of that motor plus the IR drop in its circuit. Obviously, no circuit-breaker or fuse is required as overload protection for a constant-current motor. If the motor be stalled by overload, its back-E.M.F. falls to zero; the dynamo voltage is correspondingly reduced by the action of its exciter and the constant current is maintained. The motor there-

fore continues to exert its full torque and 'holds' its load, but the power consumption in the motor circuit is only the I^2R loss. The current through the motor being constant, the speed of the machine on light-load is controlled by reducing the field current; this is effected automatically by an auxiliary exciter dynamo direct coupled to the motor, the E.M.F. of the exciter opposing the excitation of the motor field derived from the main circuit through a regulating resistance. As the load on the motor increases, the speed of the machine decreases; the opposing E.M.F. of the exciter dynamo also decreases, owing to the reduction in speed, and the field current of the motor therefore increases automatically (apart from any adjustment of the controller), resulting in the development of increased torque. As the total load on the motors increases, the generator voltage rises automatically until a predetermined maximum is reached; any further increase in the total load, which would result in overloading the generator, is countered by an automatic decrease in the current, which has hitherto been held constant. It is thus impossible for the generator to be overloaded.

The following particulars and Figs. 264, 265 are from a description * of the Austin constant-current system as applied to the driving of capstans, winches, pumps, forced-draught fans, etc., on the P. and O. liner *Viceroy of India*.

Constant-Current Generators.—In this particular installation there are three motor-generator sets, each consisting of a 230 H.P., 220 V, 500 r.p.m. motor direct coupled to a constant-current generator and its exciter. Each generator is rated at 150 kW and delivers a constant current of 250 A at from 0 to 600 V according to the load. The connections of the constant-current generator are shown in Fig. 264. The generator is an interpole machine, and the direct-coupled exciter varies the excitation of the generator so as to maintain constant current in the main circuit. The exciter has two sets of windings and two sets of brushes. Initial excitation is obtained from one pair of brushes, under adjustable control by means of a field rheostat. Current for the main excitation of the dynamo is derived from the other set of windings and brushes. The main current of the dynamo passes through coils on the exciter poles and has a balancing influence on the primary excitation. The set is started with the dynamo short-circuited, i.e. on no-load, and the exciter rheostat is adjusted to obtain the correct line current. Motors can then be switched into the main circuit. When the main current tends to decrease the primary excitation predominates in the exciter, and the excitation of the dynamo field is increased. Conversely, when the main current tends to increase, the excitation of the dynamo field is reduced until balance is restored.

* 'The Austin Constant-Current System,' D. Smeaton Munro, *El. Rev.*, Vol. 104, p. 554.

Distribution.—Energy distribution is by a simple series circuit consisting of a single-core cable passing from the generator to all the motors in series and back to

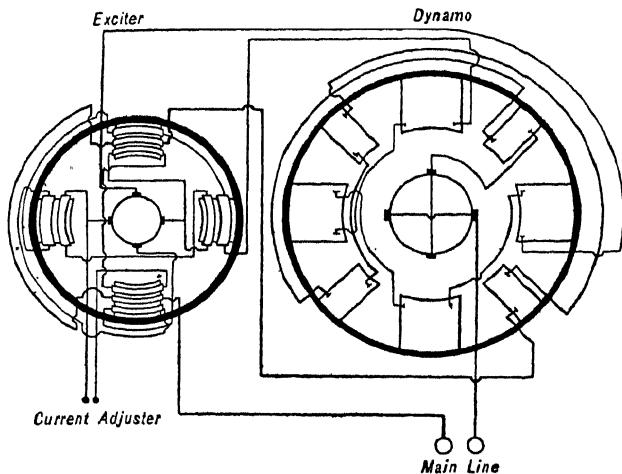


FIG. 264.—Connections of Austin constant-current generator and exciter; for the supply of constant-current D.C. motors (see Fig. 265).

the generator. For ship service 'Osmotite' cable is recommended; the primary insulation is lead sheathed and a layer of secondary insulation, proof against moisture and salt spray, is interposed between the lead sheath and the armoring.

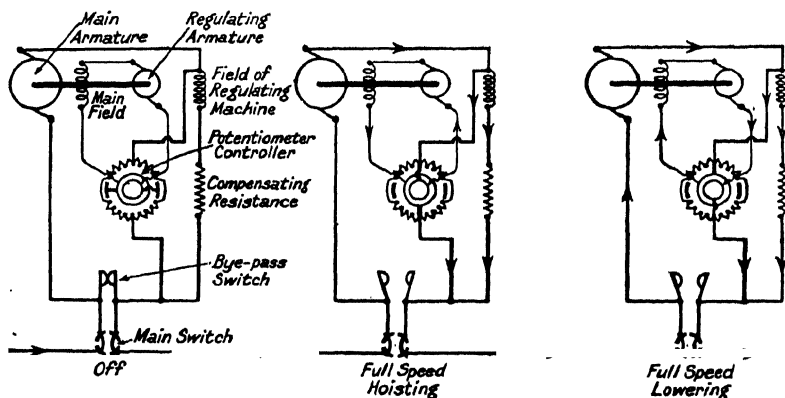


FIG. 265.—Connections of Austin constant-current D.C. motor; off, full-speed forward and full-speed reverse.

Constant-Current Motors.—Each motor has a regulating machine on the same shaft. The connections are as shown in Fig. 265. The field of the main motor is connected, in series with the armature of the regulating machine, across the rings

of a potentiometer controller as shown. The regulating machine opposes the voltage tapped by the controller and thus controls the speed of the main motor under variable load, as already explained. Maximum torque is reached when the motor is stalled because the current in the main motor armature has still the constant value, and the field strength is now a maximum because the regulating armature (being stationary) develops no opposing E.M.F. in this circuit.

Though it is not apparently adaptable to general industrial driving, the constant-current system has obvious advantages in hoisting, hauling and similar services. The characteristics of the constant-current D.C. motor resemble those of a steam engine in regard to its ability to operate over the full range of speeds at all loads.

679. Synchronous A.C. Motors. The synchronous A.C. motor is essentially a synchronous alternator reversed in action, *i.e.* converting electrical into mechanical energy. A.C. supply—usually 3-phase, sometimes 2-phase and rarely 1-phase*—is fed to the stator windings and produces a rotating magnetic field in the case of polyphase machines (pulsating in the case of single-phase machines). The rotor is provided with field coils excited by D.C. and when this magnet system is once rotating at the same speed as the stator field and in correct polarity relation therewith, it is magnetically 'locked' with and carried round by the rotating field of the stator. The motor shaft is then capable of driving any mechanical load which is not sufficiently heavy to break the magnetic lock between the stator field and the rotor. If the magnetic lock between stator field and rotor is broken, by excessive load torque, failure of D.C. excitation or any other cause, the motor 'pulls out of step' and stops.† Clearly, the synchronous motor is definitely a constant-speed machine, the speed in any particular case being determined by the number of poles and the frequency of supply.‡ If p be the number of *pairs* of poles, and f the supply frequency in cycles/sec., the speed in r.p.m. is: $N = 60f/p$. Table 117 shows values calculated from this formula.

* Single-phase motors are relatively heavy because the stator winding occupies only a small part of the total space available.

† Except in the case of the synchronous-asynchronous motor (§ 696) which can continue to run as an induction motor and may subsequently pull back into synchronism.

‡ In ordinary practice, the frequency of supply is constant, but there is no special difficulty in providing for two different numbers of poles, thus securing a two-speed synchronous motor (§ 722).

It will be seen that there is a definite upper limit to the speed of the synchronous motor for each frequency of supply, *viz.* the speed corresponding to 1 pair of poles (a two-pole machine). On the other hand, by increasing the number of poles, it is easy to reach low speeds of running; this is often an important advantage, particularly as the synchronous motor can always be operated at unity or leading P.F., whereas the P.F. of the induction motor becomes low at low speeds.

TABLE 117.—*Speeds of A.C. Synchronous Motors.**

No. of Poles.	No. of Pairs of Poles.	Speed, in R.P.M., at Supply Frequency/sec.			
		25 Cycles.	40 Cycles.	50 Cycles.	60 Cycles.
2	1	1 500	2 400	3 000	3 600
4	2	750	1 200	1 500	1 800
6	3	500	800	1 000	1 200
8	4	375	600	750	900
10	5	300	480	600	720
12	6	250	400	500	600
14	7	214·3	342·9	428·6	514·3
16	8	187·5	300	375	450
18	9	166·7	266·7	333·3	400
20	10	150	240	300	360

The action of a synchronous motor would be unaffected by placing the D.C. magnet system on the stator and the A.C. windings on the rotor, but the other arrangement is usual and offers the important practical advantage that the A.C. windings when stationary on the stator can be connected directly to H.T. supply (up to, say, 11 000 V), while the D.C. windings on the rotor can be easily supplied at, say, 125 V through slip-rings on the motor shaft. The D.C. supply for excitation may be obtained from D.C. bus-bars or mains or, with greater reliability, from an exciter dynamo direct coupled to, or chain-driven from the motor itself. Sometimes self-excitation is provided by means of an auxiliary winding and commutator acting as a rotary converter.

* These are also the 'synchronous' speeds of induction motors with the same numbers of poles, the actual speeds being lower by the amount of the 'slip' (§ 681) which is very small on light-load and usually not more than 5 % at full-load (see Table 119).

P.F. of Synchronous Motors. Varying the D.C. field current of a synchronous motor does not affect the speed of the machine, but does affect the P.F. of the current taken from the A.C. mains. At any particular load there is a certain value of field current which causes the motor to operate at unity P.F., i.e. as a non-inductive load. With lower values of field current, the P.F. becomes lagging and progressively lower, i.e. the motor is a more and more inductive load; whereas higher values of field current cause the P.F. to become progressively more leading, i.e. the

machine takes a leading current from the A.C. supply (like a condenser) and can therefore be used to compensate for the lagging P.F. of induction motors and other loads. Typical motor current—field current curves for a synchronous motor are shown in Fig. 266; from their shape these are called the 'Vee-curves' of the machine. The actual field current required to maintain unity P.F. increases with the load on the machine, hence, if the field current be kept constant at the value required for unity P.F. at full-

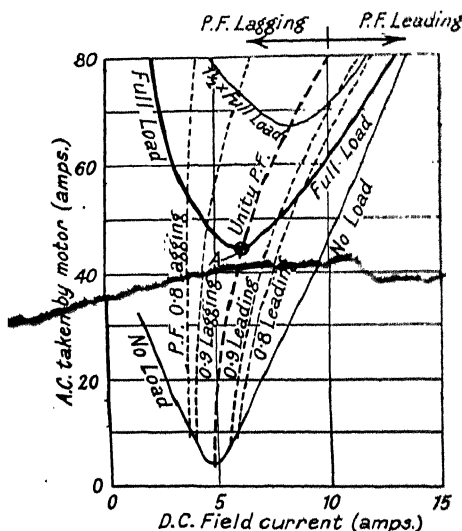


Fig. 266.—Typical vee-curves (motor current—field current) of synchronous motor. 225 H.P., 2 200 V, 6-pole machine.

load, the P.F. will be lagging at higher and leading at lower loads. This may be demonstrated by drawing a vertical line (representing constant field) through the point A, Fig. 266, but it is shown more clearly in Fig. 267 and in Fig. 268, which represent typical characteristic curves of a synchronous motor.

The efficiency of synchronous motors is usually higher than that of induction motors and their cost is lower, particularly where machines of high H.P. and low speed are concerned. Typical values of efficiency for high and low speed synchronous motors of 100 H.P. are as follows:—

H.P.	No. of Poles.	R.P.M. (60 cycles).	Efficiency % at Full Load.	
			Unity P.F.	P.F. 0.8 (Leading).
100	72	100	88	82
100	6	1 200	92½	90

The lower efficiency at the leading P.F. is due to the increased I^2R losses in the windings, owing to the heavier D.C. field current and the heavier A.C. stator current (*see* Fig. 266). The effect of the leading P.F. of the synchronous motor in compensating the lagging P.F. of other loads usually more than counterbalances the extra cost of the heavier D.C. excitation and the sacrifice of efficiency in the machine; but it should be noted that there is no

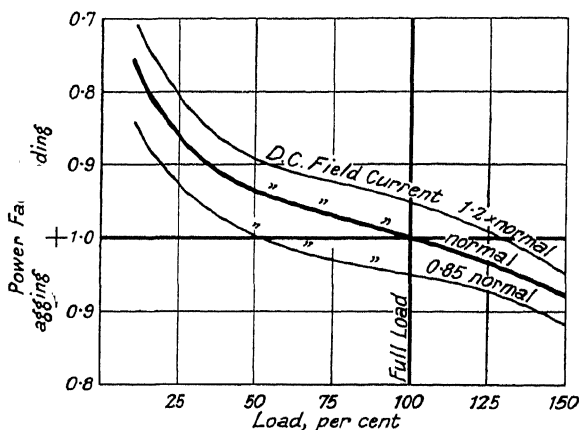


FIG. 267.—Variation of P.F. of synchronous motor with load, at different constant values of excitation.

advantage in operating a synchronous motor at leading P.F. unless: (a) in the case of private generation there are lagging loads to be compensated; (b) in the case of purchased supply the supply authority allows a rebate for high or leading P.F. A leading P.F. *per se* is just as objectionable as a lagging P.F., but under most practical conditions a leading P.F. is valuable in helping, by its compensating effect, to approach the ideal of unity P.F. throughout the system (*see also* Chap. 5, Vol. 1).

An over-excited synchronous motor is sometimes run on no-load simply as a 'synchronous condenser' (§ 160 (c), Vol. 1) to improve the P.F. of the system. A motor, however, which is driving a mechanical load can also be made to effect a useful amount of

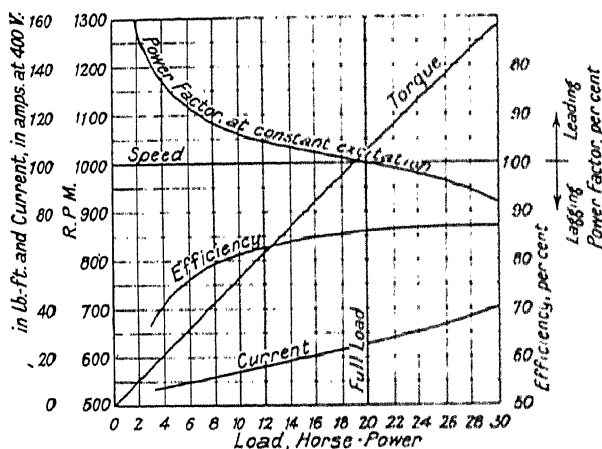


FIG. 268.—Typical characteristics of 3-phase synchronous motor. Rated output 20 H.P., 1,000 r.p.m. (see also Figs. 248, 250.)

'phase compensation' provided it is designed for the requisite range of D.C. field excitation. From this point of view, maximum results are obtained by operating the motor at 0.707 leading P.F., the watt and watless (leading or corrective kVA) components being

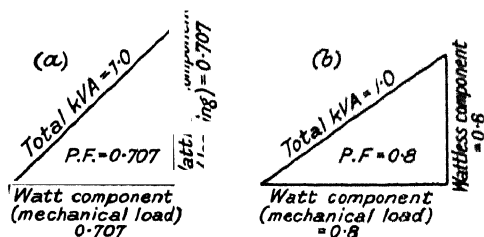


FIG. 269.—Illustrating operation of synchronous motors at leading P.F.

then equal, and the total utilisation of given combined kVA capacity being then a maximum (see Fig. 269 (a)). Nearly as great total utilisation is effected by operating at 0.8 leading P.F. (Fig. 269 (b)) and in practice it is usual to build synchronous motors to one of

two ratings: (a) unity P.F. machines which operate at unity P.F. at full-load with normal field current; (b) 80 % P.F. machines which operate at 0.8 leading P.F. at full-load with normal field current. The unity P.F. machine can only raise the average P.F. of the system to which it is connected, but the 80 % P.F. motor exercises a definite corrective effect. An 80 % P.F. motor is about 25 % larger than a unity P.F. machine of equal H.P. and its leading or capacity kVA effect is 60 % of its total kVA rating (Fig. 269 (b)), or 75 % of the watt component corresponding to its mechanical load.

For a given mechanical output, corresponding to the watt component, Fig. 269, the total kVA rating of the motor increases as follows:—

Mechanical Output (Assumed.)	P.F. of Motor.	Total kVA Rating of Motor.*	Corrective (Leading) kVA.*	Additional Total kVA Rating (com- pared with Unit P.F.) per Corrective kVA.
100 %	1.0	100 %	nil	
100 %	0.8 leading	125 %	75 %	0.33
100 %	0.707 leading	141.4 %	100 %	0.41

The A.C. current taken from the line is, of course, a minimum at unity P.F. (Fig. 266), but under the usual conditions of practice it is worth while to increase this current in order to improve the P.F. of the system as a whole. It should always pay the owner of a private generating plant to do this, but the user of purchased current has no considerable incentive to improve the P.F. of his load unless the supply tariff takes account of this factor (§ 274, Vol. 1).

The use of synchronous motors for P.F. correction is discussed more fully in Vol. 1, § 160 (c). For their application to be effective and economical in this service, the synchronous motors must be reasonably near the source of low P.F. (*e.g.* induction motors), they must be in service during the same periods as the latter, and they should be in as large units as possible (preferably not less than

* As percentage of mechanical kVA.

100 H.P.), otherwise the cost of the D.C. excitation will be relatively high.

Interesting comparisons between synchronous motors and other A.C. motors capable of operating at unity or leading P.F. are given in § 695.

Torque Characteristics of Synchronous Motors. The starting torque of the plain synchronous motor * is practically zero, being only that due to interaction between the rotating A.C. field and the eddy currents induced thereby in the pole faces of the D.C. magnet system. Such a motor is hardly self-starting under any conditions, and certainly not against a mechanical load. The only method of starting it would usually be to run it up to speed by means of an auxiliary motor and then synchronise it with the supply in the same way as an alternator (§ 149, Vol. 1); the load would then be coupled to the motor by means of a suitable clutch. Formerly, synchronous motors were subject to this inconvenience, and, as a consequence, their applications were very restricted.† Now, however, almost every synchronous motor is self-starting (by means described below), and this type of machine is used freely, on account of its valuable P.F. characteristics, wherever a constant speed of driving is either desired or acceptable.

Once a synchronous motor is running synchronously it will carry any load at constant speed (*see* Fig. 268) until the torque is sufficient to break the magnetic 'lock' between the rotating A.C. field and the D.C. magnet system. When this occurs the rotor immediately falls out of step and the machine stops unless the peak load was of such short duration that the rotor can be pulled back into phase with the A.C. field before it has slowed down appreciably.‡ The maximum overload capacity of the machine increases with the value of the D.C. field current, until magnetic saturation is reached; up to this point, the 'locking' action between the rotating A.C.

* *I.e.* a motor embodying a rotating A.C. field and a D.C. magnet system but with no provision for developing a useful starting torque.

† The driving of A.C.-D.C. motor-generator sets was one of the principal applications of such motors. The A.C. machine could be started from the D.C. end of the set, by using the D.C. generator temporarily as a motor, and, in this case, no clutch was required.

‡ As explained in § 696, the synchronous-asynchronous motor can continue to run as an induction motor, after it has pulled out of synchronism, provided that the overload is not too severe.

field and the rotor increases with the D.C. field current. Under favourable circumstances a synchronous motor can carry a momentary load of $1\frac{3}{4}$ to $2\frac{1}{4}$ times its rated H.P. without pulling out of step.

When running synchronously (as distinct from asynchronous running during the starting period), the maximum or pull-out torque of a synchronous motor varies with the D.C. field and the A.C. supply voltage, instead of with the square of the latter as in the case of induction motors. This is a distinct advantage where the supply voltage is apt to be low. For example, $12\frac{1}{2}\%$ decrease in voltage reduces the maximum torque of a synchronous motor to $87\frac{1}{2}\%$ of its full-voltage value, whereas that of an induction motor would be reduced to $(87\frac{1}{2})^2 / 100$ or $76\frac{1}{2}\%$.

A synchronous motor can be reversed by interchanging two of the stator supply leads (in the case of a 3-ph. machine) so as to reverse the direction of rotation of the A.C. field. If this be done while the motor is running, the machine is 'plugged,' *i.e.* stopped by reversal of torque; this is a method which imposes heavy mechanical stresses on the motor and on the driven load. Dynamic braking may be effected by disconnecting the stator from the supply mains and short-circuiting the stator terminals through suitable resistances, the D.C. field being meanwhile maintained; the motor is then, in effect, a heavily loaded alternator driven only by its own kinetic energy and that of the coupled mechanical load.

Though, from the nature of the case, each pole of the D.C. magnet system of a synchronous motor must keep in step with the corresponding pole of the rotating A.C. field, there is a small phase angle between the two corresponding to the drag or resisting torque of the driven load. This angular displacement varies with the load on the motor and, if the load changes suddenly, the inertia of the moving parts prevents the rotor from moving immediately to the correct new position with regard to the rotating field. There is an initial lag, followed by 'overshooting' in the opposite direction and then by more or less prolonged oscillation on either side of the correct phase position. This phenomenon is known as *hunting* and it may become very troublesome if there are cyclic variations in the load, particularly if these happen to coincide with the frequency of oscillation of the rotor and/or variations in the supply frequency. In order to 'damp' the oscillations, damping or *amortisseur* windings may be provided on the rotor. These consist either of brass or copper rings surrounding the pole shoes, or

a complete 'squirrel-cage' of bars let into the pole shoes and short-circuited by a copper ring at each end. In either case the energy dissipated by the short-circuit currents flowing in the damping winding brakes the movement (hunting) which generates these currents.

The damping windings necessary to oppose hunting* have the important effect of improving the starting characteristics of the synchronous motor, for, during the starting period, they act as the squirrel-cage rotor of an induction motor and the machine starts substantially as an induction motor. Indeed, by providing a suitably designed winding on a cylindrical rotor (*i.e.* one without the salient poles of the original type of ordinary synchronous motor), a machine is obtained which combines the merits of both the induction motor and the synchronous motor. This is the synchronous-asynchronous motor (§ 696) which has the starting characteristics of an induction motor, normally runs as a synchronous motor at unity or leading P.F. (the special rotor winding being then excited by D.C.), and continues to run as an induction motor if it is pulled out of synchronism by overload.

The earlier types of synchronous motors with damping windings in the pole faces were capable only of starting light or against not more than 10 % of full-load torque. Modern salient-pole synchronous motors with a squirrel-cage winding embedded in the pole faces will start against 30 to 50 % of full-load torque with from $1\frac{1}{4}$ to $1\frac{1}{2}$ times full-load current. The P.F. of these machines is low during the starting period owing to the long air gap and other features of design; if the starting current be reduced by using a squirrel-cage winding of high resistance, the 'pull-in' torque at synchronisation is reduced. On the other hand, the efficiency of the salient-pole synchronous motor, with a squirrel-cage starting winding in the pole shoes, is higher than that of a synchronous-asynchronous motor of equal rating. By substituting a 3-phase starting winding for the squirrel-cage winding in the pole shoes, the starting torque of the salient-pole synchronous motor can be

* When the motor is running synchronously there is no E.M.F. induced in the damping winding except when relative displacement occurs between the rotor and the rotating A.C. field. The damping winding is therefore unable to prevent such displacement or hunting, but it opposes the motion directly it occurs, and thus reduces its amplitude.

raised to about $1\frac{1}{2}$ times full-load torque; the D.C. excitation is applied after the external resistance in series with the starting winding has been removed and the full asynchronous speed has been reached. The modern synchronous-asynchronous motor with a cylindrical rotor (non-salient poles) can drive its load either synchronously or asynchronously, and has starting and pull-in torques enabling it to be used wherever a slip-ring induction motor would be applicable.

The maximum speed at which a synchronous motor can operate is that corresponding to a 2-pole construction, *i.e.* $60f$ r.p.m., where f = frequency of supply in cycles/sec. A 2-pole synchronous motor on 50-cycle supply runs at 3 000 r.p.m., and large machines of this type have been developed for such services as driving centrifugal compressors. Their construction closely resembles that of 2-pole turbo alternators, a starting winding being added to allow the machine to start as a squirrel-cage induction motor. *

The following particulars are from a paper by D. W. McLennan and I. H. Summers.*

A squirrel-cage starting winding consisting of thin deep conductors is let into special slots in the pole faces of the rotor and into recesses on the sides of the slots containing the D.C. field windings. A symmetrically distributed starting winding is thus obtained which does not interfere with the withdrawal of the main field winding should this be necessary. The retaining wedges are cut into short lengths insulated from each other to prevent induced currents flowing axially along them for the whole length of the rotor. Even so, the leakage flux from the starting winding causes a current to flow axially along the top of each length of wedge and back along the bottom. By using steel and non-magnetic wedges in different arrangements, different effective resistances and reactances can be obtained, thus varying the characteristics of the motor to some extent.

Typical current-speed and torque-speed curves for a 1 500 H.P., 3 600 r.p.m., 60-cycle motor are shown in Figs. 270 and 271 respectively. The torque is well maintained up to a speed very near to synchronism, thus making it easy to synchronise the motor. At 100 % voltage, the machine to which Fig. 271 relates, develops 150 % torque at 98 % speed, and 130 % torque at 75 % speed; hence, if the machine falls out of synchronism owing to a temporary drop in voltage, it is capable of re-synchronising against full-load when normal voltage is restored. The period for which a 2-pole synchronous motor can operate as an induction motor is very limited, owing to the rapid heating which occurs. The pull-out torque (maximum synchronous torque) is about $1\frac{1}{2}$ times full-load torque in machines operating at 1.0 P.F.; and twice full-load torque in machines operating at 0.8 leading P.F.

* *Journ. Amer. I.E.E.*, Vol. 47, p. 585.

In the latter case, full-load torque can be carried momentarily with the line voltage only 50 % of the normal value.

The synchronous characteristics of the 2-pole motor are similar to those of multipolar machines but the power required for excitation is very low, e.g. only 18.5 kW for a 2 500 H.P., 0.9 P.F., 3 000 r.p.m., 60-cycle machine. Windage loss is necessarily high at such high speeds, but efficiencies of 94.5-95.5 % have been obtained from 1 250-3 000 H.P. machines.

In sizes smaller than 800-1 000 H.P. the synchronous motor hardly competes with the squirrel-cage or wound-rotor induction motor at 3 000-3 600 r.p.m., unless the possibility of correcting power factor justifies the higher cost of the 2-pole synchronous motor. Difficulties are experienced at the slip-rings of high-power, high-speed, wound-rotor induction motors and the cost of auxiliary equipment for power-factor correction has generally to be incurred where these machines are used. Two-pole synchronous motors have been designed (in 1928) up to 7 000 H.P. at 3 600 r.p.m., 60-cycles and 4 000 H.P. at 1 500 r.p.m., 25-cycles.

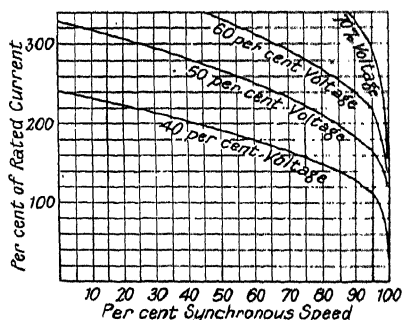


FIG. 270.—Armature current-speed characteristics of two-pole synchronous motor at various voltages.

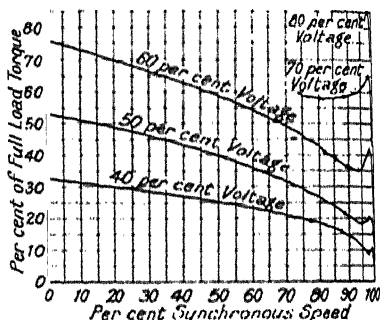


FIG. 271.—Torque-speed characteristics of two-pole synchronous motor at various voltages.

The starting of synchronous motors by electrical methods and also by allowing the stator to rotate during the starting period is explained in § 722.

Summary of Characteristics and Applications.—The synchronous motor is definitely a constant-speed machine. This is often a very desirable characteristic, but the property which is most responsible for the ever-widening application of synchronous motors is their ability to operate at unity or leading P.F. Synchronous motors are sometimes run without mechanical load simply for P.F.-correcting purposes, and are then known as 'synchronous condensers.' Usually the motor may advantageously carry a mechanical load at the same time (§ 160, Vol. 1).

Improvements in design have led to the adoption of synchronous motors in a great variety of industrial services. If the machine

is to carry very heavy overloads (up to, say, three times full-load torque) without pulling out of step, the synchronous-asynchronous type (§ 696) must be used. Synchronous motors are specially advantageous for direct-coupled low-speed driving, the P.F. of low-speed induction motors being low; high-speed (2-pole) synchronous motors are, however, available if required for such purposes as driving centrifugal pumps. Whereas the P.F. of an induction motor rapidly becomes worse at fractional loads, that of a synchronous motor leads to a greater extent as the load is reduced. Synchronous motors can be built economically for speeds down to 100 r.p.m. or so. Sizes as small as 20 H.P. are coming into use, but the most advantageous applications are generally in sizes from 100 H.P. up to 10 000 H.P. or even higher. High voltage supply at 2 200, 3 300, 6 600 or even 15 000 V can be used without a step-down transformer in motors of 200 H.P. or more. In the smaller sizes, 20 to 50 H.P., as built for driving small ammonia compressors, the field system sometimes rotates outside the stator.

Among the principal applications of synchronous motors are: motor-generator sets, frequency changers, compressors, large fans, pumps, refrigerating machines, power-house auxiliaries such as condensate and air pumps, lineshafts, cement mills, rubber calenders, and constant-speed rolling mills. A magnetic clutch may be needed if the starting conditions are very severe. Table 118* shows typical characteristics of synchronous motors used for various drives.

Synchronous motors are now used to drive many brass and copper rolling mills, and continuous sheet and bar steel mills. They are frequently used to drive non-reversing rolling mills which would formerly have been driven by induction motors carrying flywheels to smooth out the peak loads. Similarly, in heavy reversing mill drives it was formerly considered essential to employ a flywheel motor-generator set driven by an induction motor with slip-regulator, but a synchronous motor generator is now often employed to convert the A.C. supply to D.C. for the reversing mill motor. No flywheel is used where the synchronous motor is employed (the latter being a constant-speed machine), hence the peak loads are transferred to the A.C. mains with their

* F. W. Hotchkiss, *Power*, Sept. 4, 1928.

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TABLE 118.—*Industrial Applications of Synchronous Motors.*

Drive.	Motor Rating.	Starting Characteristics.				Pull-in Characteristics at Full Line Voltage.		
	H.P.	R.P.M.	P.F.	Full-Load Torque.	Line Voltage	Full-Load Current.	Full-Load Torque.	% Full-Load Current.
Seven flour mill roll stands	300	600	1.0	105	80	385	100	350
Rubber mill line	250	90	1.0	90	100	452	46	249
Rubber reclaiming hog	300*	900	0.9	112	65	368	256	490
Brass and copper rolls	350	109	1.0	55	100	286	24	169
ditto,	100	600	1.0	88	80	330	54	195
Hammer mill in cement works	250§	720	1.0	150	100	550	115	
Rock crusher	250	450	0.8	115	80	375		
				75	65	248	100	250
					35	72		

* Pull-out torque = $3 \times$ full-load torque and the machine resynchronises when the load falls to $1\frac{1}{2} \times$ full-load.

§ Carries 600 H.P. at rated voltage without pulling out of step, carries full rated load as an induction motor for 5 mins., and resynchronises when the load falls below 290 H.P., when using a frequency-relay control for the D.C. field.

amplitude undiminished. Where the supply system is capable of sustaining these fluctuations of load without voltage-regulation or other difficulties, the synchronous motor eliminates the capital cost of the flywheel and the energy losses due to flywheel windage and I^2R loss in the slip regulator of the induction motor. Also, there is no automatic gear required to maintain the voltage of the D.C. generators; the latter now run at constant speed instead of being slowed down on load as in a flywheel set. At the same time, the advantage of high power factor is secured—say 0.95 as against 0.75-0.8 where an induction motor is used. On the other hand, the H.P. of the synchronous motor must be perhaps 60 % higher than that of the induction motor which, in conjunction with a flywheel, could take its place. The synchronous motor will easily withstand peak loads of 100 % *i.e.* twice full-load.

For example, if a 1 600 H.P. induction motor were required in conjunction with a flywheel capable of delivering 3 600 H.P. temporarily, it would probably be sufficient to use a 2 600 H.P. synchronous motor which, at 100 % overload, would deliver the same peak output, 5 200 H.P.

It should be noted that although the peak load on the mains is greater (perhaps twice as great) with the synchronous motor drive than where a flywheel storage set is used, it is, in rolling mill service, of very short duration and hence is unlikely to affect the 'integrated' 5, 10 or 15 min. demand * on which maximum demand tariffs are commonly based. Even in colliery winding service, where the peak loads are of longer duration, it is doubtful whether they would persist long enough to affect the 'integrated' maximum demand. Allowing for the higher overall efficiency of the drive when flywheel storage is eliminated it is quite possible for the 'integrated' maximum demand to be reduced, notwithstanding the higher instantaneous peaks of the synchronous motor drive.

A flywheel on the shaft of a synchronous motor will not help the latter over peak loads in the same way that it would help, say, a compound-wound D.C. motor, because the synchronous motor is a constant-speed machine. Nevertheless, where there is considerable cyclic irregularity in the load-torque during each and every revolution of the driven machine, as in the case of compressors, a high flywheel effect in the synchronous motor helps to equalise the load during each revolution and thus to prevent hunting or pulsation of speed and current.

680. Miniature Synchronous Motors; and 'Selsyns.'—Small synchronous motors are often used for timing purposes, driving oscillograph mirrors, synchronous recorder drums, and other applications requiring absolute constancy of speed or strictly synchronous rotation. In such cases the power required is usually negligible and the rotor may be of any non-magnetic substance with iron bars or studs let into its periphery; these inserts lock with the rotating A.C. field when the rotor is started by hand. If the rotor be a conducting disc with iron inserts, it will start as an induction motor and then pull into synchronism. Commercial motors of this type measure a few inches and weigh a few ounces.

The 'Selsyn' (self-synchronising) motor is used for transmitting signals, indicating the position of a float, or reproducing temperature or pressure indications at a distance. Two or more motors are connected in parallel and the rotor of each receiver automatically takes up the same position with regard to its stator windings as

* *I.e.* the maximum average demand during any period of 5, 10 or 15 minutes, as the case may be, as distinct from the maximum instantaneous demand.

that in which the rotor of the transmitter is placed. If the transmitting rotor were rotated continuously, the receiving rotor would rotate synchronously with it, but, in practice, the transmitter is generally moved to various definite positions by hand, or by an instrument or float chain, etc., and the receiving rotors then move instantly to corresponding positions. Each rotor consists of an H-type core with a simple coil winding; and the slip rings of the several rotors are connected in parallel to a single-phase A.C. supply (Fig. 272). The stators carry three windings connected in star and in parallel with each other. The transmitting rotor being held in any position, its alternating flux induces E.M.F.'s in each leg of the stator winding, and the receiving rotor at once moves to the corresponding position, so that the E.M.F.'s which it induces in its stator windings are equal and opposite to those in the

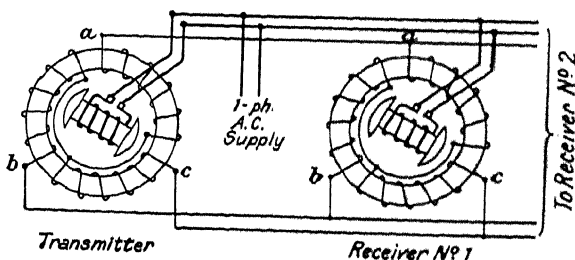


FIG. 272.—Connections of Selsyn motors.

transmitting stator. There is then no current flow between the two stators. Any desired number of receivers can be connected in parallel with a single transmitter. All the Selsyns are identical, the 'transmitter' being the one in which the rotor is forcibly moved and held, leaving the 'receivers' to repeat its movements and indications. The spindle of each rotor carries a pointer moving over a scale or signalling plate, and the size of each Selsyn is about that of a desk-fan motor.

681. Polyphase Induction Motors: General Types and Characteristics.—The A.C. induction motor is undoubtedly used more extensively than any other type of electric motor for general industrial driving. It is built in various forms which are dealt with separately in §§ 682-686; all of these depend on the same basic principles, but, by varying the design and arrangement of the component parts, widely different starting and operating character

istics are obtained. It is proposed, therefore, to state the main principles relating to all polyphase induction motors, and to make general comparisons between the main types before proceeding to individual consideration of the latter. Single-phase induction motors are dealt with separately in §§ 689 *et seq.*

The '*squirrel-cage*' induction motor is the simplest of all electrical machines, and takes its name from the form of its rotor winding which generally consists of bare or lightly insulated copper bars laid in slots in the laminated iron core and connected at each end to a ring of copper or brass. The bars being thus short-circuited at each end, this construction is often called a 'short-circuited rotor.' There is no connection from the squirrel-cage winding to any external circuit, and the bars may be very lightly insulated, or even bare, owing to the very low E.M.F. induced in them and the low resistance of the short-circuited bars.* The absence of slip rings, commutator, and any form of sliding contact reduces the upkeep of the motor to a minimum, and is a special advantage when the machine is to be used in dusty or explosive atmospheres. The stator winding is practically identical with that of a polyphase alternator. The air gap is extremely short (of the order of a hundredth of an inch), hence the bearings must be kept in good condition to prevent the rotor from fouling the stator; ball or roller bearings are specially advantageous from this point of view, and should be used wherever possible. The cost of a squirrel-cage motor is only about two-thirds that of a D.C. motor or slip-ring induction motor.

As explained below, the principal limitation of the ordinary squirrel-cage motor is its low starting torque per ampere of starting current. This objection may be overcome by the use of a special type of squirrel-cage machine (see later), or by using a '*phase-wound*' rotor (generally termed a 'wound rotor'), with windings arranged like those on the stator and connected to slip rings, between the brushes of which external resistance is connected during the starting period. When the machine has reached full speed the slip rings are usually short-circuited,† and the motor is

* See note, p. 160.

† Sometimes resistance is connected between the slip rings during normal running for speed control (§ 725), and in other cases the slip rings are connected to an auxiliary commutator machine, instead of resistances, for purposes of P.F. correction or speed control (§§ 687, 694).

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then substantially the same as a squirrel-cage machine. For an obvious reason, this type of motor is often called a 'slip-ring induction motor.'

Typical performance characteristics of squirrel-cage and slip-ring motors are shown in Fig. 273.

Electrically, the induction motor (whether of the squirrel-cage or slip-ring type) is simply a transformer with the primary windings connected to the mains and the secondary windings short-circuited.

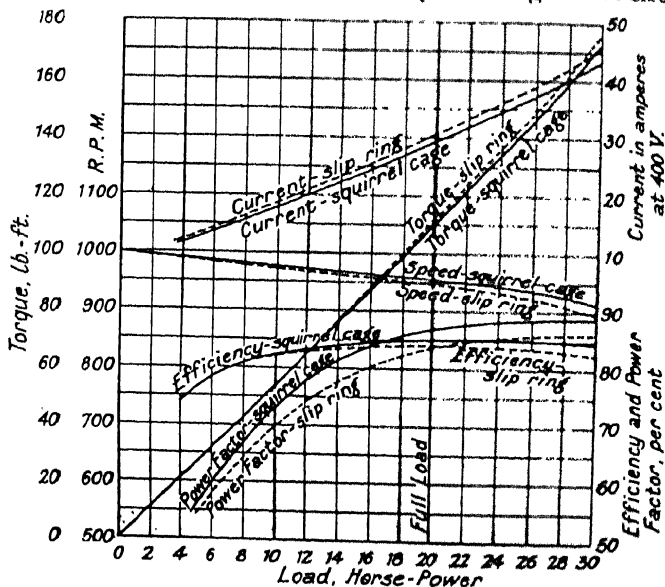


Fig. 273.—Typical characteristics of 8-ph. induction motors. Rated output 20 H.P., 950 r.p.m. (see also Figs. 248, 250, 251).

Usually the primary windings are on the stator and the secondary on the rotor, but this arrangement is sometimes reversed, and slip rings must then be used to connect the primary windings to the supply. With the usual arrangement of the primary windings, on the stator, they can be connected directly to high-voltage supply if desired.* The polyphase primary windings set up a rotating

*Induction motors up to 5 000 H.P. or so are connected to mains at up to 11 000 V without transformers. Sometimes 2 200 V supply is connected directly to 75 to 100 H.P. motors; on the other hand, 220 V supply may be used for 100 to 150 H.P. motors in damp and dirty situations or where high voltage cables are not permissible.

resultant field and this induces a current in the secondary windings; interaction between the primary field and the secondary current furnishes the driving torque of the motor. At starting, when the rotor is stationary, the frequency of the induced secondary current equals the frequency of the A.C. supply (say, 50 cycles per sec.), but, as the rotor accelerates, the relative speed between the primary field and the secondary windings decreases and, with it, the frequency of the secondary current. If the rotor ran synchronously with the rotating field, the latter would be stationary with regard to the secondary windings. There would, therefore, be no current induced in the latter and the motor would develop no torque. For this reason, it is impossible for an induction motor ever to run at synchronous speed.* On no-load, the speed approaches synchronism very closely, but, as the load increases the speed falls somewhat, to an extent comparable with the speed-drop of a D.C. shunt-wound motor. At any moment the difference in speed, or the 'slip' between the rotating field and the rotor is that required to induce the secondary E.M.F. which, in turn, produces the secondary current needed to develop the requisite driving torque, by interaction with the primary field. The machine slows up, on load, until this result is accomplished, unless the load exceeds the maximum or 'pull-out' torque of the machine (usually $2\frac{1}{2}$ to 3 times the full-load torque), in which case the motor stops and is said to be 'stalled.' A stalled squirrel-cage motor usually draws about six times its full-load current from the mains.

At normal full-load the difference between the speed of the primary field, *i.e.* the 'synchronous speed' of the motor, and the actual speed of the rotor is usually from 2 to 4 % of the synchronous speed in large, and from 6 to 10 % in small, induction motors, according to the design of the machine (*see* Table 119).

The synchronous speed of a motor with p pairs of poles (= number of poles / 2), running on a supply frequency of f cycles/sec., is $60f / p$ r.p.m. If the actual speed of the rotor be n r.p.m., the percentage slip is

$$s = \frac{(60f / p) - n}{60f / p} \times 100 = \frac{100 (60f - pn)}{60f} \%$$

of the synchronous speed. Conversely,

$$n = \frac{60f \left(1 - \frac{s}{100}\right)}{p} \text{ r.p.m.}$$

* Unless the secondary windings are excited not merely by induction but by current conducted from an independent supply, or from a special exciting winding, in which case the motor no longer runs as an induction machine.

Obviously, the frequency of the induced secondary current (*i.e.* the rotor current in the motor as usually arranged) is the same percentage of the supply frequency, as the slip is of the synchronous speed. For example, if the rotor runs with 5 % slip and the supply frequency is 50 cycles/sec., the frequency of the rotor current is 5 % of 50 = $2\frac{1}{2}$ cycles/sec.

As explained above, the slip of an induction motor is required in order that an E.M.F. may be induced, of sufficient magnitude to produce the current needed to develop the driving torque. If the resistance of the rotor winding be increased, the induced E.M.F. must also be increased to maintain a given value of current, *i.e.* the 'slip' of the rotor increases. In slip-ring motors, extra resistance is sometimes introduced into the rotor circuit in order to increase the slip, *i.e.* retard the rotor, and thus make possible the utilisation of flywheel effect. External resistance thus introduced into the rotor circuit may be used for purposes of speed control (§ 725), but the method is wasteful of energy and results in increased variation of speed with load (*cf.* speed variation of D.C. shunt motor by resistance in the armature circuit, § 675). The power input to an induction motor varies with the torque developed, not with the speed, and therefore not with the power output; in the case of a constant-torque load, if the speed be halved by resistance in the rotor circuit, the output is halved but the input remains unchanged (ignoring subsidiary losses), hence the efficiency is approximately halved; *see*, for example, Figs. 356, § 725, and *cf.* Table 134, § 726, for case of variable-torque load.

Usually the energy of the 'slip current' in the secondary of an induction motor is dissipated in the form of I^2R heat in the rotor windings and external resistance, if any, but this energy can be utilised in an auxiliary machine (§§ 687, 694). Normally its frequency and voltage are very low, but if the auxiliary machine is used to effect speed control, the frequency of the rotor current is increased as the speed of the machine is decreased.

If an induction motor be driven mechanically, by an 'over-taking' load or otherwise, at higher than its synchronous speed it operates as an asynchronous alternator (§ 144, Vol. 1) and returns energy to the A.C. supply mains. In other words *regenerative braking* is effected; *see also* later remarks concerning Fig. 276.

Reversal of a 3-phase induction motor is effected by interchanging the supply leads to two of the primary (stator) terminals or, in a 2-phase motor, by interchanging the phases of the supply. The effect, in either case, is to reverse the direction of rotation of the resultant primary field, and hence the direction of the driving torque.

Once a polyphase induction motor is up to speed it will continue running as a single-phase motor if the circuit in one phase be interrupted by any cause. During such *single-phase operation* the efficiency is low and the current in the primary and secondary circuits is unduly heavy. In the case of slip-ring motors an overload trip coil may be provided in the rotor circuit, but this is impossible in squirrel-cage motors and reliance must then be placed on the fuses or overload trips of the stator, and these may not operate before the rotor current has reached a value causing excessive heating. A 3-phase motor running with an open-circuit in one stator phase will usually carry about 70 % of full-load without overheating and its pull-out torque may be $1\frac{1}{2}$ to 2 times the rated full-load torque. A slip-ring motor will continue to run (but not start) with one rotor phase interrupted, but the pull-out torque is reduced to about one-third the normal value; this fault is generally revealed by the rotor vibrating seriously.

If the number of slots in the stator and rotor of an induction motor be equal, or have a common divisor, the rotor is apt to be 'locked' magnetically by the stator field, so that poor starting torque is obtained and the starting current is heavy. In small motors the rotor slots are sometimes skewed to eliminate this action, but in most cases it is sufficient to make the number of slots unequal and with no large common divisor.

Approximate data for 25- and 50-cycle, squirrel-cage and slip-ring induction motors are given in Table 119. These data are on a conservative basis suitable for general estimating purposes, and higher efficiencies can be guaranteed in particular cases.

As will be seen from Fig. 273, the *power factor* of an induction motor decreases rapidly at fractional loads, and underloaded induction motors are one of the principal causes of low P.F. in A.C. supply networks.

Though the low-power factor of induction motors on light load lowers the average P.F. of the whole installation (back to the point, if any, where phase-compensating equipment is situated),

it must not be thought that the wattless consumption of the motor is greater on light load than on full load. Actually, the wattless consumption increases with the load on the machine over the greater part of the range, but the watt component increases at a much greater rate, hence the P.F. improves; the low P.F. on light loads is due to the wattless consumption remaining about constant below 50% of full load, whereas the true power consumption (kW) decreases steadily with the load.

These points are illustrated by Fig. 274, which shows the kW, total kVA and wattless kVA inputs of a typical induction motor at various loads.

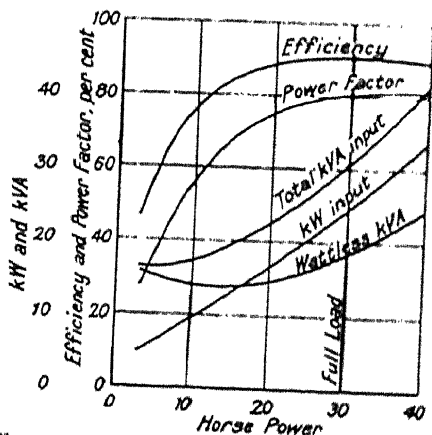


FIG. 274.—Illustrating variation of input (kW, total kVA and wattless kVA) to induction motor.

At 30 H.P. the efficiency is about 84%, and the power input is therefore

$$30 \div 0.84 = 35.7 \text{ kW.}$$

The P.F. is about 0.8, hence the total kVA input is $35.7 / 0.8$ or 44.6 kVA, and the wattless consumption Total $\text{kVA} \sqrt{1 - (\text{power factor})^2}$ is $44.6 \sqrt{1 - (0.8)^2}$ or 28.5 kVA.

Similarly, at 10 H.P. the efficiency is about 76%, corresponding to 18.5 kW input. The P.F. is about 0.56, hence the total input is 33.2 kVA; and the wattless consumption is 24.2 kVA approx. Thus, though the mechanical output of the motor has been reduced by 66% (from 30

H.P. to 10 H.P.), the wattless consumption is reduced only by $(28.5 - 24.2) \times 100 / 28.5$ or 23.2%; and the power factor suffers from the increased relative importance of the wattless component.

The P.F. of an induction motor is also affected greatly by the number of poles in the primary. A high-speed motor (*i.e.* one with a small number of poles) has a much higher P.F. than a low-speed motor. For this reason *low-speed induction motors should be avoided* wherever possible; either a direct coupled synchronous motor or a high-speed induction motor driving through reduction gearing is much to be preferred from this point of view.

Electrically, an induction motor is equivalent to a transformer with a magnetic circuit of high reluctance, high leakage, and therefore relatively high magnetising current. The actual value of the magnetising current, which determines the P.F. of

the machine, varies mainly with the length of the air gap and the pitch of the poles. The minimum practicable length of air-gap is determined by mechanical considerations. Other factors being equal, the P.F. is higher the greater the pole-pitch, *i.e.* the fewer the number of poles and, therefore, the higher the speed of the machine.

An additional argument for the use of high-speed motors is the lower cost per H.P.; on the other hand, the initial rush of current at starting is heavier in high-speed motors.

Fig. 275 shows typical values of P.F. at full-load for induction motors of various H.P. and speeds.

Commercial induction motors are usually guaranteed to carry their rated load when either the voltage or the frequency varies

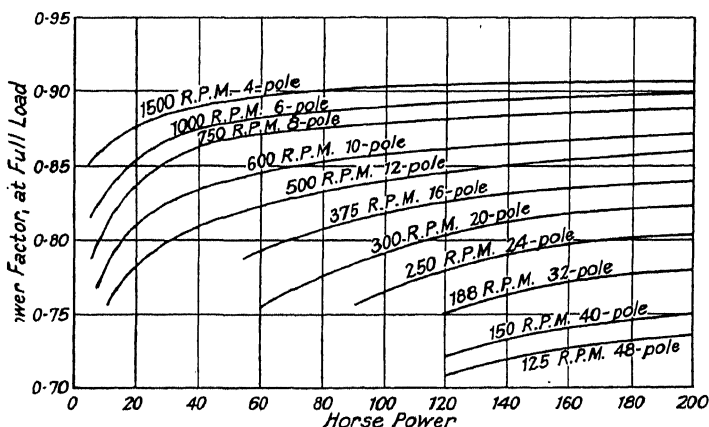


FIG. 275.—Typical P.F. of 3-phase motors at full load, for various horse-powers and speeds.

$\pm 10\%$ from normal. An induction motor operated on other than its rated frequency of supply is capable of developing its rated torque if the voltage be altered in the same ratio as the frequency.

For example, a 220 V, 40-cycle motor rated at 10 H.P., 760 r.p.m., could be operated on 25-cycle supply at $220 \times 25 / 40$ or 137½ V and would then run at about 460 r.p.m. and develop $10 \times 460 / 760$ or about 6 H.P. If operated on 60-cycle supply at $220 \times 60 / 40$ or 330 V, the motor would run at about 1 160 r.p.m. and develop $10 \times 1.160 / 760$ or about 15 H.P.

Low voltage results in a decreased speed (*i.e.* increased slip) in an induction motor, and usually in a slight improvement in power factor and a larger decrease in efficiency. Typical data, at full load, are as follows:—

	Slip %	Power Factor	Efficiency %
At rated voltage	2.8	0.93	90
At 95% " "	3.4	0.935	89
At 90% " "	3.6	0.94	88

The most important effect of voltage variation is on the torque of the motor. (Other factors being constant, the torque of an induction motor varies with the square of the voltage applied to the primary windings. This fact is specially important when starting the motor and when operating it on overload.)

For example, if the voltage applied to the stator be reduced to 60% of normal, either by series resistance or by autotransformer, in order to reduce the value of the starting current, the torque developed by the motor is only $(0.6)^2$ or 0.36 of what it would be if full line voltage were applied. Similarly, if the motor is capable of carrying $2\frac{1}{2}$ times full-load torque when supplied at full voltage, it will only carry $(0.85)^2 \times 2\frac{1}{2}$ or 1.8 times full load torque if the voltage at the motor terminals be 85% of the rated value, i.e. if there be 15% voltage drop due, for example, to transformers, supply conductors, etc., being too small to supply the overload at rated voltage.

The effect of reduced voltage on the torque of an induction motor has thus an important bearing on its starting characteristics (*see also* § 724); and, where induction motors are subject to severe overloads, it is important that the supply cables and transformers be of ample capacity, otherwise the voltage drop on load will seriously reduce the load which the motor can carry without pulling out of step.

Fig. 276 shows torque-speed curves at rated voltage for a 3-phase induction motor with various values of total resistance R in the rotor circuit. The actual value of resistance taken for calculating the curve marked $R = 1$ is $R = 0.1 \times$ reactance of rotor at full supply frequency (this being the frequency of the rotor currents when the rotor is stationary). The torque-speed curve for a squirrel-cage motor is usually between the curves marked $R = 1$ and $R = 2$ in Fig. 276; the other curves, for higher values of R , are such as might be obtained for a slip-ring motor with various values of external resistance connected between the slip rings, i.e. in series with the rotor windings. If the torque-speed curve for a particular motor with the rotor short-circuited were as marked $R = 1$, Fig. 276, the torque-speed curves corresponding to the use of such external resistance as would double, treble, quintuple, etc.,

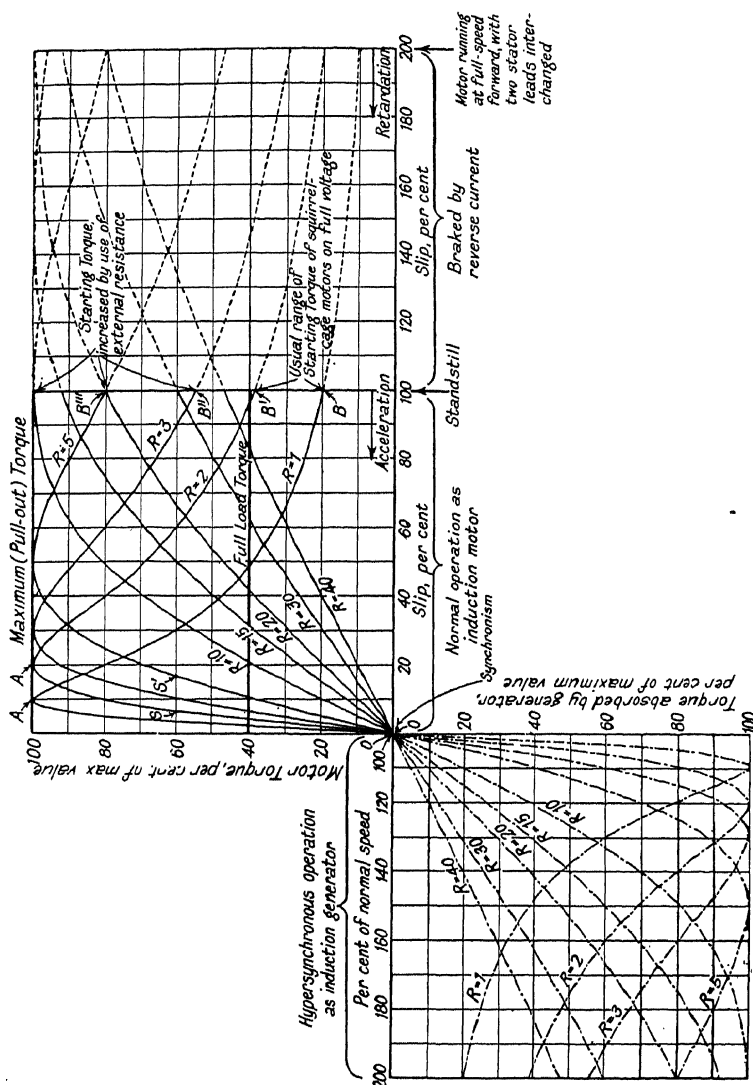


Fig. 276.—Torque-speed curves for 3-phase slip-ring induction motor with various values of rotor circuit resistance.

the total resistance in the rotor circuit can be obtained by multiplying the *abscissa* of the curve $R = 1$ by 2, 3, 5, etc.

The solid-line curves in Fig. 276 relate to the normal operation of the machine as a motor; the dotted curves to the right relate to the braking of the running motor by reversal of the stator phase-rotation (by interchanging two stator leads), and the chain-dotted curves, in the lower left-hand part of the figure, relate to the driving of the machine at speeds above synchronism by an 'overtaking' load (*e.g.* a load being lowered by a crane), the machine then operating as an induction generator (*see also* § 144, Vol. 1).

A number of interesting characteristics of the induction motor can be observed from Fig. 276. Thus the solid curves relating to normal operation of the machine as a motor show the small decrease in speed that occurs as the torque increases, when the rotor resistance is low (*e.g.* $R = 1$), until the maximum or pull-out torque is reached. At this point, A, A' , etc., the operation of the motor is unstable because the slightest further increase in load will result in the speed decreasing and, as the motor torque is thus reduced, there will be a further decrease in speed, and so on, the motor coming to rest under the conditions represented by B, B' , etc. The value of the maximum torque is independent of the value of R , but the decrease in speed with increasing torque becomes greater as the resistance R is increased. In other words, the speed at a given load is lower the higher the rotor resistance; and the effect of load variation on the speed is greater the higher the rotor resistance (*see also* Fig. 357).

The effect of increased rotor resistance in raising the starting torque is shown at B, B' , etc. (Fig. 276); the curve $R = 10$, corresponding to a rotor resistance equal to the rotor reactance at full supply frequency, gives a starting torque equal to the maximum or pull-out torque of the machine. By inserting resistance in series with the rotor, the speed at any load can be reduced, *e.g.* from $S = 95\frac{1}{2}\%$ of synchronism to $S' = 88\%$ of synchronism at 60% of maximum torque, by increasing R in the ratio 2:5, but this method is wasteful, the whole of the energy dissipated in the resistance being converted to heat.* Also, with the higher value of resistance, the motor speed will change more rapidly as the load varies.

The curves relating to braking by reversed current show that, at each speed, there is a certain value of resistance R resulting in maximum braking torque. If the latter is to be maintained during the whole period of retardation, the resistance must be reduced as the speed falls.

When the machine is running as an asynchronous generator, at higher than synchronous speed, the speed remains nearly constant at all values of torque so long as the rotor is short-circuited, but rises rapidly with the torque if there is much resistance in series with the rotor. In other words, an 'overtaking' load may cause an induction motor to race unless the rotor is short-circuited.

Special Types of Induction Motors. The general arrangement and electrical design of induction motors are subject to

* If the rotor runs with $s\%$ slip, the rotor output = $(100 - s)\%$ of the rotor input.

various modifications in order to obtain different starting characteristics, and more or less speed control. The methods of starting and control are further discussed in §§ 723 *et seq.*, present consideration being limited to the effects of these methods on the operating characteristics of the machines.

If started on full line voltage, an ordinary squirrel-cage induction motor develops a starting torque equal to from 0.8 to 1.2 times full-load torque with from 5 to 7 times full-load current at a P.F. of about 0.45. Such a current rush is usually only permissible in the case of relatively small motors and, in any case, it results in such a high IR drop in the motor supply leads (unless the latter are unduly large) that the voltage at the motor terminals falls considerably below normal; the torque, which varies with the square of the voltage, then decreases correspondingly.

In order to reduce the starting current, squirrel-cage motors are generally started on reduced voltage, either by an auto-transformer, or by star-delta switching of the windings of a 3-phase motor (equivalent to starting on $1/\sqrt{3}$ or about 58 % of line voltage), or by series-parallel switching in the case of a 2-phase motor (equivalent to starting on half the line voltage).^{*} The effect is then to reduce both the starting torque and the starting current taken from the mains approximately in proportion to the square of the voltage applied to the motor.[†] Thus an ordinary squirrel-cage motor developing about $1\frac{1}{2}$ times full-load torque on starting with a current of about $6\frac{1}{2}$ times full-load value at full line voltage, would have the following starting characteristics at reduced voltage:—

Applied voltage, % of line voltage	50 *	57.7 †	60	70	80
Starting torque, % of full-load torque	30	42	45	54	62
Starting current, % of full-load current	150	165	225	305	410

* Corresponding to series-parallel switching of 2-ph. motor.

† Corresponding to star-delta switching of 3-ph. motor.

* If either star-delta or series-parallel switching is to be employed this must be stated when ordering the machine, because the necessary connections must be led out from the phases of the stator windings.

† If the applied voltage be reduced by series resistance, the line current is reduced in the same ratio as the voltage, and *not* as the square of the voltage; see § 724.

If the machine were of a high torque type developing a higher torque per ampere on full voltage, its characteristics on reduced voltage would also be improved.

By using a wound-rotor machine and inserting external resistance in series with the slip rings, the starting torque can be increased (see Fig. 276), and about full-load torque can be developed at starting with about $1\frac{1}{2}$ times the full-load current, up to twice full-load torque with about $2\frac{1}{2}$ times the full-load current. The P.F. and efficiency are usually lower in slip-ring than in squirrel-cage motors of equal horse-power (see Table 119).

A squirrel-cage winding of high resistance would give increased starting torque but at the cost of low efficiency during normal running. One method of combining the high starting torque of a high-resistance squirrel-cage with the efficiency of a low-resistance winding, consists in using a centrifugal switch to parallel sections of the winding which are in series when the motor is stationary or running at any speed up to 70 to 80 % of synchronism. Motors of this type can be arranged to develop up to 2 or $2\frac{1}{2}$ times full-load torque at starting, with from 2 to 3 times full-load current, but, compared with the ordinary squirrel-cage machine, there is the cost and complication of the centrifugal switch.

A squirrel-cage motor of fixed high rotor-resistance may be used if efficiency is a secondary consideration and it is desired to obtain a high value of slip so that advantage can be taken of flywheel-storage without using a wound rotor and slip-regulating resistance. Such motors are also particularly useful in hoisting service where high starting torque is very desirable and maximum efficiency is of secondary importance owing to the intermittency of operation. The particular machine of this type represented in Fig. 277 develops nearly 3 times full-load torque at starting, with about $5\frac{1}{2}$ times full-load current.

By using deep rotor bars of low resistance but high reactance, the starting current of a squirrel-cage motor can be much reduced, whilst retaining practically the same starting torque as that of an ordinary low-resistance, low-reactance machine. For example, on full line voltage the high reactance motor develops about $1\frac{1}{2}$ to $1\frac{3}{4}$ times full-load torque with $4\frac{1}{2}$ to 5 times full-load current, both the torque and the current being reduced about proportionately to the square of the voltage if the machine is started by means of an auto-transformer.

In order to combine high starting torque with high efficiency during normal running, use may be made of the double squirrel-cage rotor, carrying a high-resistance winding near the surface of the rotor and a low-resistance winding embedded more deeply. The high-frequency rotor current during the starting period is practically confined to the outer, high-resistance winding (by the high reactance of the embedded winding) and therefore develops a high starting torque, whereas the low-resistance winding carries most of the current during normal running and results in high efficiency. A motor of this type can be used where a wound-rotor machine would otherwise be needed.

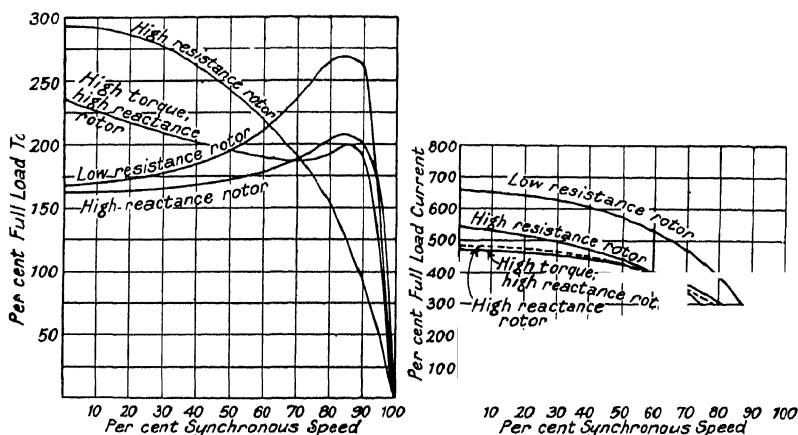


FIG. 277.—Torque-speed and current-speed curves for typical squirrel-cage motors.

Fig. 277, from a paper by C. W. Falls,* shows how widely the characteristics of different types of squirrel-cage motors vary from one another. As a corollary, it is important that squirrel-cage motors be selected to suit the intended application; no squirrel-cage motor, whether standard or special, is suitable for all classes of work.

Summary of Characteristics and Applications.—In that its speed decreases slightly (only a few per cent.) between no-load and full-load, the A.C. induction motor resembles the D.C. shunt-wound motor. With a short-circuited or 'squirrel-cage' rotor the

* Jour. Amer. I.E.E., 1928; *Power House*, Sept. 20, 1928.

induction motor is the simplest of all electric motors, but its starting torque is relatively low. By using a high resistance rotor winding, a double rotor winding or a phase-wound rotor with slip rings and a variable external resistance, the starting torque can be improved at the expense of some loss of efficiency (where a high resistance winding is employed) or some increase in complexity (where slip rings and an external rheostat are used). Regulable resistance in the rotor circuit during normal running gives the machine a drooping load-speed characteristic resembling that of the D.C. compound-wound motor and enables a flywheel to be used effectively. The same result may be obtained more efficiently by using an auxiliary machine (§ 728), instead of ohmic resistance, to regulate the slip of the rotor. Unlike D.C. shunt- and compound wound motors, the A.C. induction motor cannot be varied in speed continuously and efficiently. A few definite speeds can be obtained efficiently by pole-changing connections. Continuous variation of speed can be obtained by means of variable resistance in the rotor circuit, but there is a serious waste of energy in this resistance, and the speed of the motor corresponding to any particular value of the resistance varies with the load.

Owing to its freedom from sliding contacts the squirrel-cage induction motor is specially suitable for use in explosive atmospheres, a clutch being used if necessary to permit the motor to start on light load. The plain induction motor is applicable to most industrial drives excepting those where continuous regulation of speed is required; while the induction motor with slip regulator is applicable to driving planers, shears, punches, guillotines, winding engines and other fluctuating loads to which flywheel storage can be usefully applied. In order to avoid the cost and complication of a slip-regulator, a high-resistance, squirrel-cage motor may be used, or a slip-ring motor may be provided with sufficient resistance between the rings to produce from 10 to 15 % slip on overload.

682. Squirrel-Cage Polyphase Induction Motors. The main features of squirrel-cage motors are dealt with in the preceding general paragraph on induction motors. From the user's point of view the chief merit of squirrel-cage machines is that they are the simplest, cheapest and most robust type of electric motor, there being no moving contacts, unless a centrifugal switch is used to improve the starting characteristics (§ 681). The rotor winding consists only of lightly insulated bars brazed to end rings, or even

of a wrapping of bare copper sheet punched and bent so as to form 'bars' and end rings all in one piece with only a longitudinal joint where the ends of the wrapping meet. In pony motors, as used for starting rotary converters, the rotor is of solid steel with grooves milled along the surface so as to leave, in effect, a squirrel-cage winding integral with the body of the rotor (*see note, p. 160*).

The most serious objection to the squirrel-cage motor is that it is not a variable-speed machine; this is a definite limitation which is only partially removed by the use of pole-changing windings to obtain two or more different speeds in a fixed ratio.

The former objection that squirrel-cage motors developed low starting torque and required heavy starting current is now overcome by means explained in § 681. If required, a squirrel-cage motor can now be obtained with starting and running characteristics practically equal to those of a slip-ring machine.

In some places in this country the regulations of the electricity supply authorities restrict the use of squirrel-cage motors to sizes not exceeding 5 to 20 H.P., as the case may be. In the United States, on the other hand, squirrel-cage motors are used in sizes up to 200 H.P., and there is no reason why such machines should not be allowed in any large industrial supply system, subject to suitable regulations as to the design of the motor and the conditions of starting. No authority which supplies current to electric arc furnaces, for instance, can reasonably object to the use of squirrel-cage induction motors of any H.P. which the user is likely to desire. In the meantime, instead of enforcing an arbitrary limit to the size of squirrel-cage motors, it seems reasonable to limit the use of the latter only in terms of the maximum demand of the consumer during normal operation of his load. In other words, if the starting of a motor does not increase the maximum demand beyond the value which it would otherwise have, there seems to be no reason why that motor should not be employed.

This basis of dealing with squirrel-cage motor loads is discussed in a paper by D. B. Hoseason (*Jour. I.E.E.*, Vol. 66, p. 410).

Suppose that the maximum current consumption of a consumer (corresponding to the total H.P. installed) = I amperes; that the full-load current of the largest motor = $\frac{1}{n} \cdot I$ amperes; and that the average load at any moment $\frac{5}{4} \times$ connected load.

Then, if the whole load except the largest motor be connected, the average current

demand at that moment $\frac{3}{4}(I + \frac{1}{n}I)$ amperes. Suppose now that the motor is started; if the total current is not to exceed I amperes, the starting current of the largest motor must not exceed

$$I - \frac{3}{4}(I + \frac{1}{n}I) = \frac{1}{4}I = \frac{I}{4n} \left(\frac{n}{4} - 3 \right) \text{ amps.}$$

But the full load current of the largest motor $\frac{I}{n}$ amperes, being the starting current of this machine must not exceed $(\frac{n}{4} + \frac{3}{4})$ times the full load current of the motor if the consumer's maximum demand is not to be increased above I amperes.

A corresponding relation can be worked out in the same way to suit any other ratios between the maximum and mean demands and the connected load.

As explained in § 681 squirrel-cage motors of appropriate design can be applied to almost any load for which slip-ring motors are suitable. According to requirements, the speed regulation of the squirrel-cage machine can be made to resemble that of a D.C. shunt or compound wound motor, and the machine is applicable to much the same services except that continuous speed variation cannot be obtained. Squirrel-cage motors are regularly built in sizes up to several hundred H.P. for direct supply at pressures up to 6 600 or even 11 000 V; yet larger sizes can be built if the conditions of starting permit their use. So-called 'high frequency' induction motors, *i.e.* motors operating on a supply frequency of 150 to 200 cycles per sec., are used extensively for driving portable tools (*see* § 774).

The control of squirrel-cage motors is discussed in §§ 724-726.

683. Slip-ring Polyphase Induction Motors. The general principles and characteristic of these motors are covered by § 681. As there explained, the distinction between slip-ring and squirrel-cage motors is that the rotor of the slip-ring machine is phase-wound, the outer end of each phase being connected to a slip ring. Variable resistance connected between the brushes bearing on the slip rings enables the effective resistance of the rotor circuit to be altered for purposes of starting or speed control (*see* notes on Fig. 276, § 681). If the motor is to run for considerable periods without restarting, it is usual to provide automatic or manually-operated gear for short-circuiting the slip-rings and lifting the brushes from the latter; this saves the wear and loss occasioned by friction between rings and brushes, and by I^2R losses in the leads between the rings and an external short-circuiting point. Usually

all three rings are insulated from the shaft, and this is desirable because the star point of the external resistance for the rotor circuit is usually earthed and, if one of the slip rings be earthed (by being mounted directly on the shaft), the corresponding phase of the external resistance is short-circuited and the other two are overloaded.

Normally, the rotor is short-circuited when the motor is up to full speed, but if it is desired to utilise flywheel-storage in the driven load, a small section of the external resistance may be left permanently in series with the rotor to increase the 'slip' of the machine. Brush-lifting gear must not then be used. Sometimes resistance is left in circuit in order that the decrease in speed on overload may help to limit the amount of the overload, *e.g.* when driving centrifugal pumps having flat head-delivery curves, so that the delivery rises rapidly when the head decreases.

Generally speaking, slip-ring induction motors can be used for the same classes of service as D.C. compound motors, including the driving of lineshafts, generators, pumps, fans, compressors, lifts, rolling mills, winding engines and haulages. Continuous speed variation can be obtained by means of variable resistance in the rotor circuit, but this method is wasteful and the speed corresponding to any particular value of resistance varies with the load; also, the motor will race if the resistance in the rotor circuit is too high when the machine is being driven as a generator by a descending hoist-load (*see* Fig. 276, § 681).

Slip-ring induction motors are built in sizes up to 11 000 H.P. or so, for direct supply from 2 or 3 ph. mains at pressures up to 11 000 V.

The control of slip-ring motors is discussed in §§ 724-726.

684. Double Squirrel-Cage Induction Motors.—These machines which are sometimes called current-displacement motors or Boucherot motors (after their inventor), have in effect a double squirrel-cage winding on the rotor. Often two separate windings are actually employed, but sometimes the winding consists of single bars resembling a dumb-bell in cross-section. In the latter case, the outer portion of the conductor, near the periphery of the rotor, is of smaller cross-section than the inner portion and is connected to the latter by a thin web of metal, the complete bar being of aluminium cast into the deep and specially-shaped slots. Whatever the details of the construction, the basic

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principle is the use of one squirrel-cage winding of relatively high ohmic resistance near the surface of the rotor, and another of low ohmic resistance embedded deep in the slots and therefore offering considerable inductive resistance. At the moment of starting, the frequency of the current induced in the rotor bars equals the supply frequency and, owing to the high inductance of the embedded bars, most of the current flows in the outer bars; as these are of high ohmic resistance a relatively high starting torque is developed and the starting current is lower than that of a plain squirrel-cage machine. As the machine accelerates, the frequency of the current in the rotor winding decreases, and the current flow is gradually transferred to the inner bars of low ohmic resistance,

TABLE 120. — *Data for Double Squirrel-Cage High Torque Induction Motors.*

(By courtesy of Verity Ltd.)

50-CYCLE SUPPLY AT PRESSURES UP TO 500 V.

B.H.P.	R.P.M. at Full-Load.	Efficiency, %.			Power Factor.		
		Full-Load.	$\frac{1}{2}$ -Load.	$\frac{1}{4}$ -Load.	Full-Load.	$\frac{1}{2}$ Load.	$\frac{1}{4}$ Load.
3	1 420	85	83	80	0.83	0.80	0.70
3	940	83	82	80	0.77	0.72	0.62
3	710	80	79 $\frac{1}{2}$	77	0.75	0.69	0.59
5	1 440	86	83 $\frac{1}{2}$	81	0.84	0.81	0.72
5	950	85	84	82	0.80	0.76	0.68
4	705	81	80	78	0.75	0.69	0.59
10	1 440	87	85 $\frac{1}{2}$	83 $\frac{1}{2}$	0.87	0.85	0.78
10	955	85	84	82	0.83	0.79	0.69
12	715	85	84 $\frac{1}{2}$	82	0.82	0.78	0.68
15	1 450	89	88	87	0.88	0.86	0.80
15	955	86	85	84	0.84	0.81	0.72
15	720	87 $\frac{1}{2}$	87	86	0.83	0.80	0.70
30	1 450	89 $\frac{1}{2}$	89	87 $\frac{1}{2}$	0.88	0.86	0.80
30	965	88 $\frac{1}{2}$	87 $\frac{1}{2}$	86	0.86	0.84	0.77
30	725	87 $\frac{1}{2}$	87	86	0.85	0.81	0.70
50	1 450	90 $\frac{1}{2}$	89 $\frac{1}{2}$	87 $\frac{1}{2}$	0.90	0.89	0.85
40	965	89 $\frac{1}{2}$	88 $\frac{1}{2}$	87 $\frac{1}{2}$	0.88	0.86	0.80
45	725	89	88 $\frac{1}{2}$	87	0.87	0.83	0.71
70	1 465	92	91 $\frac{1}{2}$	89	0.90	0.89	0.85

the inductive resistance or reactance ($2\pi fL$) of the latter decreasing with the frequency of the current (§ 44, Vol. 1). At full speed, when the frequency of the rotor current is only a few cycles per sec., the greater part of the current flows in the deep, low-resistance bars. The advantage of a high-resistance rotor winding at starting is thus combined with that of a low-resistance winding during normal running. The utilisation of the current-displacement principle involves some sacrifice of power factor, efficiency and stalling torque as compared with an ordinary squirrel-cage motor.

The transfer of the induced or 'slip' current from the outer to the inner winding occurs naturally and continuously as the frequency of this current decreases, *i.e.* as the rotor accelerates. Acceleration is therefore smooth and continuous from stand-still to full-speed if the motor be started on full voltage; if star-delta or auto-transformer starting be employed there is, of course, a sudden acceleration at the moment of changing from reduced to full voltage. The lower starting current, compared with that of an ordinary squirrel-cage motor, makes the double squirrel-cage type more suitable for starting on full-line voltage, and the high starting torque is generally an even more valuable consideration.

Table 120 shows typical data for a commercial range of double-squirrel-cage motors with two independent squirrel-cage windings of copper bars. From 0.7 to 1.1 times full-load torque is obtained with from 1.3 to 1.75 times full-load current in the star position of star-delta starting.

Table 121 compares the starting performance of squirrel-cage motors with two rotor windings, with those of ordinary squirrel-cage motors and slip-ring motors respectively.*

* The data in Table 121 may be compared with the following figures given by Prof. Dr. F. Niethammer in *Z.d.V.d.I.*, Vol. 74, p. 1200. These figures show the

	Ordinary Squirrel-Cage. Up to about $7\frac{1}{2}$ kW.	Double-Bar Rotor. 10 kW Upwards.	Eddy-Current Rotor. 20 kW Upwards.
Starting torque { Delta	2.0 to 2.8	2.1 to 3.0	1.2 to 1.5
Star	0.6 to 0.8	0.7 to 1.0	0.4 to 0.5
Starting current { Delta	6.0 to 6.3	4.0 to 5.1	4.0 to 4.8
Star	2.0 to 2.1	1.3 to 1.7	1.3 to 1.6

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TABLE 121. — *Comparison between Starting Torques and Currents of Different Types of Induction Motors. (General Electric Co., Ltd.)*

Method of Starting.	Double Squirrel-Cage Motor.		Ordinary Squirrel-Cage Motor.		Slip-Ring Motor.	
	Starting Torque. Times Full-Load Torque.	Starting Current. Times Full-Load Current.	Starting Torque. Times Full-Load Torque.	Starting Current. Times Full-Load Current.	Starting Torque. Times Full-Load Torque.	Starting Current. Times Full-Load Current.
Straight on to mains	2	4 to 5	1.2		1 to	1 to 2
Star-delta switching	0.6	1½	0.4			
Auto-transformer (70% tapping)	1	2½				
Ratio: $\frac{\text{Starting Current}}{\text{Starting Torque}}$		2½				

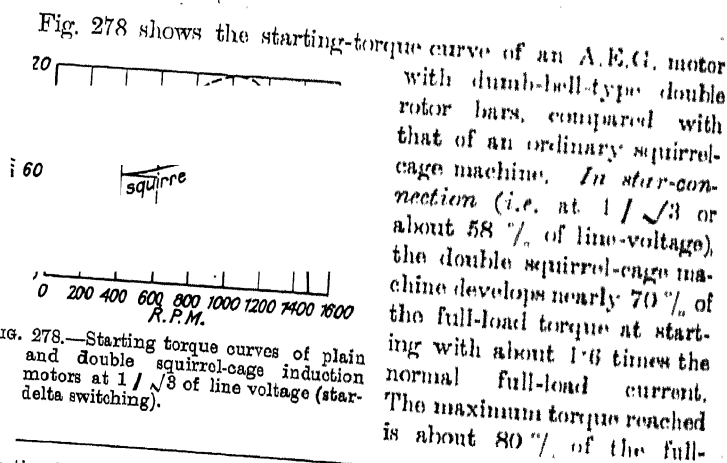


Fig. 278.—Starting torque curves of plain and double squirrel-cage induction motors at $1/\sqrt{3}$ of line voltage (star-delta switching).

starting torque and current, in terms of the rated full-load torque and current, for ordinary squirrel-cage, double-bar, and eddy-current rotors respectively, with delta- and star-connection starting in each case. The so-called eddy-current rotors have very deep conductor bars.

It will be noted that the ordinary squirrel-cage motor is here credited with higher starting torque than in Table 121. The actual characteristics in any particular case depend upon the details of design, see Fig. 277.

load torque (*cf.* 120 % for the plain squirrel-cage motor), corresponding to a pull-out torque *at full voltage*, delta-connection of 2.4 times full-load torque compared with 3.6 times full-load torque for the ordinary squirrel-cage machine represented by Fig. 278.

A single squirrel-cage winding with very deep bars gives characteristics resembling those of a double-winding machine, the effective resistance of the bars being increased by current displacement during the starting period, but the desired characteristics are developed more definitely by the use of two independent windings.

The applications of double squirrel-cage motors include the driving of compressors, grinding and pulverising machinery, belt conveyors, and other machines requiring a high starting torque.

The notes given in §§ 724-726 concerning the control of ordinary squirrel-cage motors are equally applicable to double squirrel-cage machines.

685. The Richter Induction Motor.—In the double squirrel-cage induction motor of the Boucherot type (§ 684) high starting torque and high efficiency during normal running are obtained by current displacement from one rotor winding to another in parallel with it. Substantially the same result is obtained in the Richter induction motor by a transfer of apparent resistance from one stator winding to another in series with it. The rotor is phase-wound but permanently short-circuited; no slip rings are required. The stator windings consist of a running winding wound for, say, 8 or 4 poles and a starting winding wound for a smaller number of poles (4 or 2 respectively). The rotor winding has a high resistance with regard to the starting winding on the stator, and a low resistance with regard to the running winding. During the first stages of starting, the field due to the starting winding predominates and the motor develops a high starting torque. As the machine accelerates, the voltage drop across the running winding increases and that across the starting winding decreases. When the motor has reached the speed corresponding to its running winding, the P.D. across the starting winding and the torque developed by the latter are very low; the starting winding may therefore be short-circuited. The machine then runs as an ordinary induction motor.

As usually designed, the Richter motor can be switched straight on to the supply, and the starting winding is short-circuited automatically when the machine is up to speed.

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About 1.1 times full-load torque is developed at starting with twice full-load current, and this torque is maintained practically constant during the whole period of acceleration.

686. Pole-Changing Induction Motors. The synchronous speed of any squirrel-cage or slip-ring induction motor is $60f/p$ r.p.m., where f = frequency of supply in cycles per sec., and p = the number of *pairs* of poles in the primary (usually the stator) winding; *see also* § 681. It is therefore evident that the speed of the machine can be changed by altering p , the number of pairs of poles. In order that this may be done conveniently, the stator winding must be arranged in sections, with tapplings taken out to switchgear effecting the necessary changes in connection. The number of different speeds which can be obtained in this way is generally restricted to two, three or four by considerations of complication and efficiency,* and the individual speeds being inversely proportional to the numbers of poles, the difference between them is necessarily considerable. Nevertheless, there are cases where requirements are met by a limited number of speeds over a considerable range.

For example, fans used to ventilate a vehicular tunnel between Oakland and Alameda, Calif., are driven by 3-ph., 60-cycle, 440 V, pole-changing squirrel-cage motors designed for speeds of 450, 600, 900, and 1200 r.p.m., the corresponding ratings being 5, 15, 30, and 75 H.P. respectively. Each motor has two independent stator windings, one above the other in the slots, and each of these windings is provided with middle tapplings for parallel connections. The motors are started on full-voltage when connected for 450 or 600 r.p.m. operation, and on reduced voltage when arranged for 900 or 1200 r.p.m. A time-element is introduced when slowing down from a higher to a lower speed, in order to prevent too rapid retardation of the fan.

A pole-changing motor recently developed for crane service, in order that light loads or the empty hook might be hoisted at twice the normal speed, has second stator and rotor windings. One stator winding with, say, 8 poles operates in conjunction with a slip-ring winding on the rotor to produce a synchronous speed of 750 r.p.m. on 50-cycle supply; whereas the second stator winding with 4 poles operates in conjunction with a squirrel-cage rotor winding, the synchronous speed being then 1500 r.p.m.

Another application of two-speed pole-changing induction motors is to the driving of lifts. Two separate stator windings are used, the high-speed winding of few poles being used for acceleration and normal running, and the low-speed winding of many poles for retardation and 'landing.' A powerful retarding effect

* A special method of pole-changing giving, for example, six different speeds in the range 375 to 1000 r.p.m. on 50-cycle supply, is described by F. Creedy, *Jour. I.E.E.*, Vol. 61, p. 309.

is obtained on changing over from the high-speed to the low-speed winding. Combinations giving speed ratios up to 6:1 have been used for driving express lifts in America.*

The H.P. rating of pole-changing induction motors is much reduced at the lower speeds, typical ratings being as follows:—

75/30/15/5	H.P.	at	1 200/900/600/450	r.p.m.	respectively.
100/53/26	"	"	580/480/360	"	"
120/60/25	"	"	480/360/240	"	"
1950/580/265	"	"	1 800/1 200/900	"	"

In the case of wound-rotor machines, speeds intermediate between those given by pole-changing can be obtained by inserting more or less resistance in the rotor circuit, but this involves rheostatic losses and the speed then varies considerably with the load.

Both the efficiency and the P.F. of pole-changing motors are lower with the low-speed than with the high-speed connection, and the decrease in P.F. at fractional loads is particularly serious with the low-speed connection.

687. Three-Phase Commutator for P.F. Correction and Speed Control.—The principal of P.F. correction in 3-phase induction motors by means of a 3-phase commutator or exciter may be explained by reference to Fig. 279, in which *A* represents a winding similar to that of a D.C. armature, *B* represents three sets of brushes electrically 120° apart, and *C* represents a laminated iron ring completing the magnetic circuit but carrying no winding (*see also* Plate facing p. 236, Vol. 1). The brushes are connected to the rotor slip rings of the induction motor whose P.F. is to be corrected.

Suppose that the brushes are fed with 3-phase current at a frequency f cycles per sec. The current in the winding produces a rotating field turning at an angular speed $\omega = 2\pi f$ radians per sec., and, if the winding is stationary, this field cuts its turns and produces a back-E.M.F. proportional to ω . If, however, the winding be rotated at speed ω in the same direction as the rotating field the latter will no longer cut the turns, and there will be no induced back-E.M.F. In other words, the effective self-inductance of the

* The design and application of these special machines is dealt with in a paper, 'A.C. Elevator Motors of the Squirrel-Cage Type,' by E. E. Dreese, *Jour. Amer. I.E.E.*, Jan., 1929, p. 32.

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winding is zero. If now the winding be driven at a speed ω' , greater than ω , but still in the same direction, the E.M.F. induced in the winding will be reversed in direction, i.e. the self-inductance of the winding will be, in effect, negative. This is the condition existing when the winding is driven at the speed of rotation of an induction motor, and the commutator brushes are fed with current from the induction motor rotor, at the frequency of slip. The E.M.F. induced in the winding then leads by 90° on the rotor current, i.e. it corrects the P.F. of the main motor.

This method of compensation is ineffective at the moment of starting (winding stationary) and on no-load (slip-current practically zero), but is a maximum at full-load. In practice, it enables the induction motor to be operated at unity P.F. at about $\frac{1}{2}$ -load, and

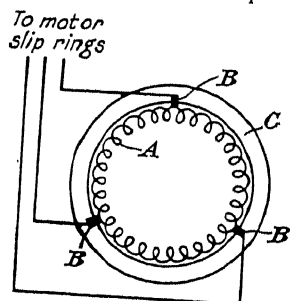


FIG. 279.—Three-phase commutator winding for P.F. correction.

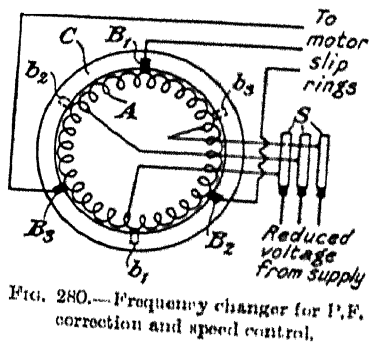


FIG. 280.—Frequency changer for P.F. correction and speed control.

at 0.97 P.F. leading at full-load. In the case of low-speed motors, the compensator is driven by a high-speed auxiliary motor, the H.P. of which is only that required to cover the excitation losses.

If the winding *A* be fed at three equidistant points through slip rings connected to the supply through a step-down transformer, we have the arrangement shown in Fig. 280. When the winding *A* is stationary it produces a rotating field, twining at angular speed $\omega = 2\pi F$ radians per sec., where F = supply frequency in cycles per sec. Under these conditions, current taken from the brushes *B* is also at the supply frequency F , but if the winding *A* be driven at a speed ω' in the opposite direction to the rotation of the field, the net speed of the latter with regard to the brushes *B* is $\omega - \omega'$ and, if ω' be the angular speed of the induction motor (i.e. if the winding *A* be driven by the induction motor), the frequency of

the current collected by the brushes B will equal the frequency of slip of the main rotor. A constant E.M.F. is thus applied to the rotor winding of the main motor at the frequency of slip of the latter, and the phase relation of this E.M.F. with regard to the E.M.F. of the rotor can be varied by shifting the brushes B . In other words, the P.F. of the main motor can be regulated.

If a second set of brushes be provided, as at b , and the phases of the main rotor be connected separately to B_1b_1 , B_2b_2 and B_3b_3 , the speed of the main motor can be regulated by altering the angular displacement between the sets of brushes B and b (§ 728).

The magnetisation of an induction motor, and therefore the power-factor 'compensation' of the machine so far as the main supply circuit is concerned is effected with lower kVA in the rotor than in the stator circuit. The ratio of the kVA required in the two cases is that of the frequencies. For example, it is only necessary to supply 1 kVA of reactive (magnetising) power at a 'slip' frequency of $2\frac{1}{2}$ cycles/sec. to obtain the same compensation as would be effected by 20 kVA at the supply frequency of 50 cycles/sec. in the stator circuit. If the 1 kVA were generated at $2\frac{1}{2}$ cycles/sec. by an auxiliary alternator, the latter would be as large as the machine required to generate 20 kVA at 50 cycles, but a much smaller commutator machine of the frequency-changer type suffices to transform 1 kVA supplied at 50 cycles to 1 kVA at $2\frac{1}{2}$ cycles/sec.

688. Auto-Compensated Polyphase Induction Motors.—

The machines here considered are polyphase induction motors in which power factor or phase correction is effected by devices incorporated in the machines themselves, as distinct from the use of static condensers, phase advancers, or other auxiliary equipment (§ 160, Vol. I, and § 728). In the ordinary induction motor, current for magnetising the machine is drawn from the A.C. supply mains, and as this current is lagging it lowers the P.F. of the machine particularly on fractional loads when the wattless magnetising current remains practically constant, but the 'wattful' current is reduced (see Fig. 274, § 681). In any case there is a certain unavoidable dissipation of energy in magnetising the motor, *viz.* the I^2R loss in the exciting windings, but the wattless kVA required for excitation decreases with the frequency of the magnetising current and is zero when this frequency is zero, *i.e.* when D.C. is used, as in a synchronous motor. If an induction

motor be excited by current generated specially for the purpose, instead of by current drawn from the A.C. mains, its P.F. with regard to the latter is unity. Also, the lower the frequency of the magnetising current, the lower the kVA required for the purpose; in other words, it is preferable to magnetise the machine by current at the low frequency of 'slip' (§ 681) rather than by current at the full supply frequency. If the excitation be effected in the secondary circuit (usually the rotor), the reactive power required equals $(s / 100) \times$ primary reactive power, where s = percentage slip; the equipment required to effect the magnetisation is therefore smaller and cheaper than it would be if the excitation were supplied to the primary circuit. This assumes that the magnetising kVA. are generated at the supply frequency (say 50 cycles) and converted to the frequency of slip (say $2\frac{1}{2}$ cycles) by a frequency-changing commutator. If the magnetising kVA. were generated at $2\frac{1}{2}$ cycles by an alternator, the latter would have to be as large as the alternator required to generate the equivalent (greater) magnetising kVA. at the supply frequency.

Where a separate phase advancer is employed, magnetising current at the low frequency of slip is supplied to the secondary circuit of the induction motor by an auxiliary machine. It is quite practicable, however, to incorporate the exciter with the motor, utilising the magnetic circuit of the latter, and this is simpler and cheaper than the use of an auxiliary exciter, particularly where motors of low or medium H.P. are concerned. Incidentally, compensation is specially desirable in such machines, for the principal cause of low P.F. in most A.C. supply systems lies in small induction motors operating at fractional loads.

The primary and secondary windings of any induction motor (usually on the stator and rotor respectively) can be interchanged if desired, the A.C. supply then being fed to a phase-wound rotor through slip rings, and the stator carrying a squirrel cage winding or a phase-winding with provision for inserting starting resistance between the several phases and the star point. The principle of auto-compensation is equally applicable to either arrangement of the motor, the commutator feeding magnetising current at slip frequency to the secondary circuit of the motor. The advantages usually claimed for the rotor-fed machine are that the commutator is smaller and sparking is less than with the stator-fed arrangement; a rotor-fed machine cannot be connected directly to high voltage

supply, but this point does not arise where small machines are concerned.

In the Heyland compensated induction motor, the main A.C. supply is to the stator, and the rotor winding is equivalent to a squirrel-cage winding and a commutator winding, the latter serving to excite the machine and being fed at network frequency through the commutator brushes. In the Osnos motor,* on the other hand, the main supply is fed to the rotor through slip rings, and the stator winding (which is now the secondary) is excited by current taken through a commutator from an auxiliary winding on the rotor (*see also* Figs. 292, *f*, *g*, and Table 124, § 695).

Many different forms of compensated induction motors have been evolved. Usually the phase correction is not operative during the starting period, and in that case the starting current of the

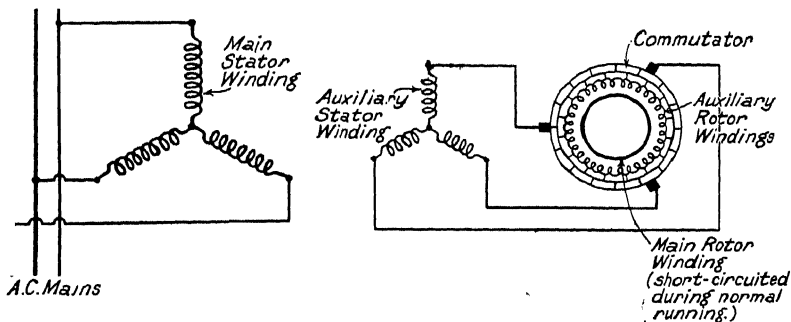


FIG. 281.—Stator-fed compensated induction motor with auxiliary stator winding supplied with magnetising current by an auxiliary winding on the rotor.

compensated motor is *relatively* heavier than that of a non-compensated machine.

When running at normal load, a compensated induction motor of unity P.F. absorbs a current $= I \cos \phi$; where I is the current absorbed at power factor $\cos \phi$ by an uncompensated induction motor on the same load. In other words, the current required by the compensated machine may be from 0.8 to 0.9 times that required by an ordinary induction motor on load. During the starting period, however, the compensated motor generally absorbs the same current as an ordinary induction motor, and whereas this may be $1\frac{1}{2}$ times the normal full-load current of the ordinary induction motor if the latter is a slip-ring motor started on full-voltage against full-load torque, it will be $1\frac{1}{2}/\cos \phi$ or from 1.4 to 1.6 times the normal full-load current of the compensated motor, and special allowance may have to be made for the *relatively* heavier starting current of the compensated machine.

*The British Thomson Houston Co.'s 'No-Lag' motors and the English Electric Co.'s 'Kosfi-Leading' motors are of the rotor-fed type, which was originally proposed by Osnos. Various practical difficulties have been overcome.

The connections of one form of stator-fed compensated induction motor with a magnetising winding on the stator are shown in Fig. 281.

The 'All Watt' compensated induction motor, made by the General Electric Co., Ltd (London), is of the Torch type and is essentially a combination of an induction motor with a Leblanc phase advancer (§ 160, Vol. I). As shown diagrammatically by Fig. 282, the machine is a stator-fed slip-ring motor with an auxiliary low-voltage winding and commutator on the rotor. The motor is started as an ordinary slip-ring machine with the

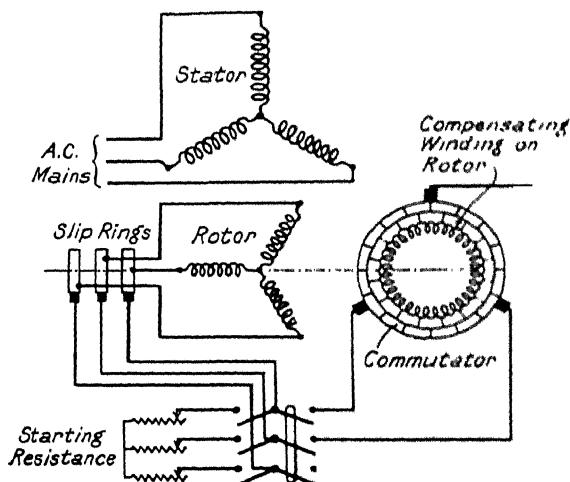


FIG. 282.—Connections of G.E.C. 'All Watt' stator-fed compensated induction motor.

compensator out of action, thus avoiding the sparking which would occur at the brushes owing to the high voltage and relatively high frequency during the starting period. When the motor is up to speed the rotor slip rings are switched on to the commutator brushes, and the machine is self-exciting. Its P.F. is practically unity at all loads from $\frac{3}{4}$ to $1\frac{1}{4}$ times full-load, and about 0.7 at $\frac{1}{4}$ -load, as compared with, say, 0.82 at $1\frac{1}{4}$ -load, 0.78 at $\frac{3}{4}$ -load and 0.4 at $\frac{1}{4}$ -load in an ordinary induction motor.

The connections of a rotor-fed compensated induction motor are shown diagrammatically in Fig. 283. The speed of the rotating field produced by the main winding on the rotor (connected to the

slip rings) is constant with regard to the auxiliary winding connected to the commutator. The E.M.F. induced in the auxiliary winding at network frequency by transformer action is therefore independent of the actual speed of the rotor, but the frequency of the current produced in the external circuit by this E.M.F. is converted by the action of the commutator and brushes to the frequency of slip, *i.e.* to the frequency of the current induced in the stator winding. Altering the setting of the brush rocker changes the phase of the E.M.F. at the brushes, and thus permits the P.F. of the machine to be adjusted. Motors of this type are made in sizes up to about 2 000 H.P. and for direct connection to supply pressures up to 1 000 V.

Auto-compensated induction motors are started in the same way as ordinary squirrel-cage or slip-ring induction motors as the case

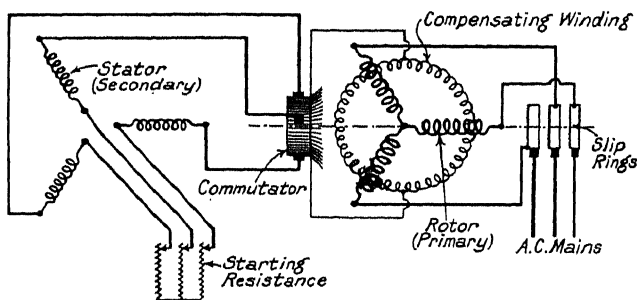


FIG. 283.—Rotor-fed compensated induction motor.

may be (§§ 723, 724). An incidental advantage of the compensation of P.F. is that the pull-out torque of the machine is increased by about 25 %.

689. Single-Phase Induction Motors.—Structurally, the single-phase induction motor resembles the polyphase induction motor (§ 681) except that the stator has only a single-phase main winding on the stator. When supplied with single-phase A.C. this winding produces a pulsating flux, *i.e.* a flux which varies from a positive to a negative maximum value along a stationary axis (that of the stator winding). When the rotor is stationary, the pulsating field of the stator winding induces equal and opposite currents in the two halves of the rotor winding, and there is no resultant starting torque. Suppose, however, that the rotor is running at synchronous speed ($60f/p$ r.p.m., where f = stator

supply frequency in cycles per sec., and p = number of pairs of poles in the stator), the conditions are then as follows:

The rotor winding may be considered as concentrated into two coils, aa , bb , at right angles to each other (Fig. 284). An E.M.F. may be produced in each of these coils in either or both of two ways, viz. by induction (transformer effect) from the stator winding or by rotation (generator action) in the field produced by the stator winding. Suppose that, in the left-hand illustration (I), the flux due to the stator winding is a maximum. The rate of change of the flux being momentarily zero there is no E.M.F. induced in aa and, as aa is moving parallel to the flux at this moment, there is also no E.M.F. of rotation generated at this moment. The conditions are

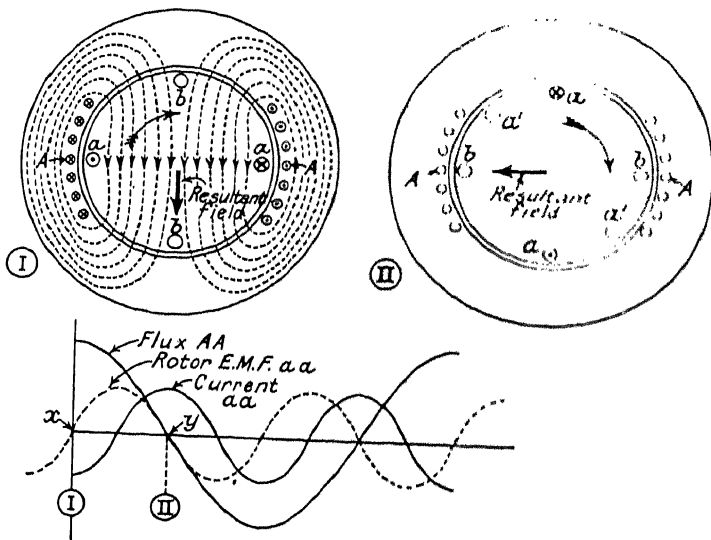


FIG. 284.—Illustrating the action of a single-phase induction motor.

therefore represented by the point x in the lower part of Fig. 284. A quarter of a cycle later (the cycle here referred to being that of the stator supply) the stator flux is zero, see (II), Fig. 284. As the rotor is running synchronously, by hypothesis, the coil aa will now be in the position shown. The E.M.F. induced in aa is now zero because the coil is perpendicular to AA ; and the E.M.F. of rotation is zero because the flux is zero. These conditions are represented by point y in the lower figure. In other words, the E.M.F. in aa has passed from a zero x , through a maximum (at a position $a'a'$), to a zero y during one-quarter of a cycle of the stator current; the frequency of the rotor E.M.F. is therefore twice that of the stator current. The current produced by this E.M.F. in the highly inductive circuit of the rotor lags nearly 90° , as shown in the lower diagram. The current aa is a maximum four times per revolution, twice when the flux AA is a maximum and twice when it is zero.

If the number of turns, n , on stator and rotor be equal, the E.M.F.'s in each are equal, but the rotor current is only half the stator current I ($= E/(2\pi fL)$) for the rotor frequency is twice the stator frequency. When the coil aa is in the position shown at (I), Fig. 284, the current induced in it opposes the stator ampere-turns and the resultant field is $\frac{1}{2}In$. A quarter of a revolution later, when aa is in the position shown at (II), Fig. 284, the stator field is zero but the rotor ampere-turns $= \frac{1}{2}In$, producing a resultant field of the same strength as before but in a direction at right angles to the resultant field in (I). Continuing this reasoning, it will be seen that the combined effect of aa and AA is to produce a uniform rotating field, when the rotor is running at synchronous speed.

The case of coil bb can be considered in the same way, this producing torque when the torque developed by aa is zero.

From the above it will be seen that there is a uniform rotating field in a single-phase induction motor when the latter is running at synchronous speed. Actually, the rotor must run at slightly lower than synchronous speed, the difference between the synchronous and the actual speeds being the 'slip' (§ 681). At less than synchronous speed there is still a rotating field, but it is no longer of constant strength and, with the rotor stationary, we reach the limiting case of a unidirectional, pulsating field.

An alternative method of considering the action of a single-phase induction motor is by regarding the single-phase pulsating field as being the resultant of two fields rotating in opposite directions at equal speed, each having a constant magnitude equal to half the maximum value of the single-phase field. This way of looking at the problem facilitates the derivation of the torque curve (§ 730), but although the hypothetical oppositely rotating fields are mathematically equivalent to the actual field, they do not in fact exist.

In order to start a single-phase induction motor, it is necessary to employ auxiliary means to set up a rotating field. One method, the 'split-phase' method, of doing this is to provide a starting winding in the stator, the axis of this winding being electrically at right angles to that of the main stator winding. The single-phase supply is connected to both windings (in series or in parallel, according to the method employed), and as nearly as possible 90° difference of phase is produced between the currents in the two windings by one or other of various alternative connections of resistances (or condensers) and inductances. The machine then starts substantially as a two-phase motor, and the starting winding is disconnected when the rotor is up to normal speed (*see also* §§ 690, 730).

The direction of running of a single-phase induction motor depends simply upon the direction in which it is started, *i.e.* upon

the direction of rotation of the field produced by the main and starting windings. Reversed rotation is obtained by reversing the connections of either the starting or the running winding (but not both).

The speed of a single-phase slip-ring motor can be varied by inserting more or less resistance in the rotor circuit but the efficiency decreases rapidly as the slip increases, and the motor is liable to stall if the speed be reduced more than 15 to 20 % by this means. The maximum torque decreases as the resistance is increased.

The older types of single-phase induction motor developed very low starting torques, say 10 to 15 % of full-load torque with $1\frac{1}{2}$ to 2 times full-load current in the case of squirrel-cage machines, and about 20 % of full-load torque with 1 to $1\frac{1}{4}$ times full-load current in the case of slip-ring motors. The normal operating characteristics are generally similar to those for 3-phase induction motors (Fig. 273) but the P.F. at full-load is about 3 % lower, and the efficiency about 5 % lower than for a 3-phase machine (*see also* Figs. 247, 250, 251). The output of an ordinary single-phase induction motor is usually from two-thirds to three-fourths that of a polyphase motor of the same dimensions.

The better characteristics obtainable by using a pole-changing stator in conjunction with a dual-resistance rotor are noted in § 691 (Parkinson 'Tork' Motor).

A standard 3-phase motor can be used on single-phase supply, two methods being illustrated in Fig. 285.* In the method represented by the left-hand diagram, the switch *S* is opened after the motor has been brought up to speed, thus disconnecting the inductance *L*, resistance *R*, and third-phase *C*. The method shown by the right-hand diagram uses an auto-transformer *T* and a condenser *K* connected as shown to phase *A* or *B* (according to the direction of rotation desired), and left permanently in circuit.

It is stated (*ibid.*) that a 220 V, 100-cycle, 6-pole, 1-H.P. motor started by this method developed 14 % of full-load torque at starting. The efficiency was 66 %, and the P.F. 0.54 at rated output, falling to 60 % and 0.49 respectively when the condenser was removed.

* *See also* for further methods 'Operation of Polyphase Motors from Single-Phase Supply,' G. Windred, *El. Rev.*, Vol. 98, p. 527.

Whereas the starting winding of the ordinary single-phase motor, with 'split-phase' starting, is disconnected as soon as the machine reaches full-speed, a special condenser-type single-phase induction motor (§ 690) has been developed with two stator windings, both of which are in circuit as long as the machine is connected to the supply. A static condenser connected permanently in circuit enables the motor to develop a relatively high starting torque, and improves the P.F. of the machine during normal operation. Where specially high starting torque is required, extra condenser capacity is employed and part of this is disconnected automatically after the machine has accelerated. It is claimed that these motors can be 'plugged' and reversed from full speed at any load by the use of a 3-pole reversing switch. Owing to the fact that the condenser-type single-phase motor is

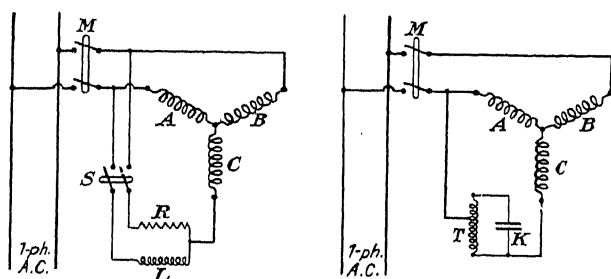


FIG. 285.—Operation of polyphase motors on single-phase supply.

capable of developing the same torque as a polyphase motor with about 70 % of the current, it is specially suitable for switching straight on to the mains. Its applications include the driving of lifts, hoists, machine tools, a variety of reversible drives, and also variable speed applications in the smaller sizes.

Motors of this type are built in sizes up to about 30 H.P. for synchronous speeds from 250 to 3 000 r.p.m. on 50-cycle supply. The P.F. correcting effect of the condenser is specially valuable in the case of low-speed machines.

690. Split-Phase and Condenser-Type Single-Phase Induction Motors.—As usually arranged, the split-phase single-phase motor has a squirrel-cage rotor and a 2-phase winding on the stator. The connections of the latter are shown diagrammatically in Fig. 286,

A being the main or running winding and B a starting winding. In order to produce phase displacement between the currents in A and B , thus producing the effect of a 2-phase supply and establishing a rotating resultant field, the B circuit contains a relatively high non-inductive resistance R . Generally, R is provided by using finer wire for the B winding than for A . The rotor having been brought up to running speed by the rotating field maintained during the starting period, the switch S is opened (usually automatically by a centrifugal device) and the motor continues to run in the pulsating single-phase field produced by the winding A . For true 2-phase operation during starting, the angle θ , Fig. 286, should be 90° , but this cannot be obtained simply by adding resistance in one phase. The ampere-turns in A being fixed by the design of the machine, the starting torque increases with the ampere-turns of B , which may be increased by reducing the number of turns in B (because I_B varies inversely with the square of this number of

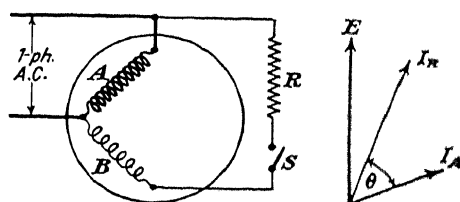


FIG. 286.—Diagrammatic representation of split-phase 1-ph. motor.

turns). The resultant current also increases as I_B is increased. A starting torque of $1\frac{1}{2}$ to 2 times full-load torque can be obtained, but the starting current is 2 to $2\frac{1}{2}$ times that of a 3-phase squirrel-cage motor.

If a condenser be used instead of the resistance R , Fig. 286, in series with the starting winding, the phase angle θ can be made nearly 90° . The starting torque for given values of I_A , I_B is thus increased and the resultant current, besides being smaller than before, is also nearly in phase with the voltage OE . In other words, the starting torque per ampere is increased, as compared with the ordinary split-phase motor, and the P.F. of the machine whilst starting is nearly unity. The condenser, or part of it, remains in circuit during normal running, thus raising the overall P.F. of the machine on full-load; if desired, the P.F. can thus be raised to unity or a leading value, but, in order that the condenser may not be unduly large, it is inadvisable to raise the corrected P.F. above about 0.95 lagging (see Fig. 45, § 159, Vol. 1).

The characteristics, design and construction of the condenser-

type, split-phase, single-phase motor are fully discussed in a paper by B. F. Bailey,* from which the following notes are extracted:—

The condenser-type single-phase motor develops about the same starting torque as a polyphase induction motor with about 70 % as much starting current. The starting torque can be increased, if necessary, by reducing the number of turns in the auxiliary winding; but, generally, the motor will develop sufficient starting torque when the auxiliary winding has more turns than the main winding, and a smaller condenser can then be used. By choosing a suitable capacity for the condenser, the currents in the two windings of the stator are made practically in quadrature and their resultant (the line current) may be in phase with the line voltage; the motor then operates internally as a 2-phase machine, but at unity P.F. single-phase so far as the supply is concerned.

With a condenser of that capacity, which gives best all-round performance of the motor under normal load, the starting torque is about 50 % of full-load torque.

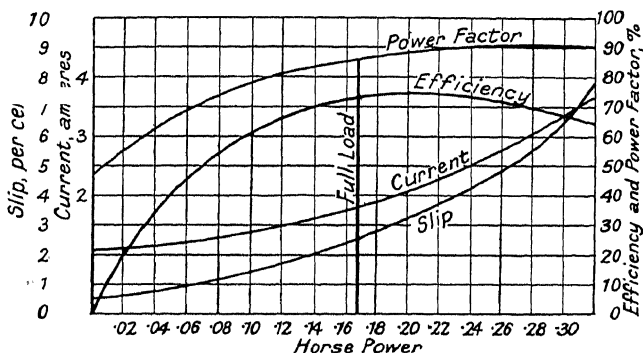


FIG. 287.—Characteristic curves of condenser-type single-phase motor.

Rating: $\frac{1}{4}$ H.P., 1 800 r.p.m., 1-ph., 60-cycles, 110 V. Capacity used $10\mu F$. Pull-out torque 232 %. Max. locked torque 320 %. Locked current 12.2 A.

This is sufficient for such loads as fans, centrifugal pumps and grinders, but, for most purposes, a larger capacity is needed during starting than during normal operation. If the condenser used during starting has several times the capacity of that used during normal running a starting torque of from 2 to 4 times full-load torque can be obtained. The supplementary condenser, used in parallel with the 'running' condenser during the starting period, may be an electrolytic condenser, *e.g.* 'formed plates of aluminium immersed in borax solution. Such a condenser is cheap and its high losses are of minor importance because the condenser is in circuit only during the starting period. Where only a moderate starting torque is required, and a relatively heavy starting current is not objectionable, a resistance may be connected in parallel with the 'running' condenser during the starting period; the characteristics obtained are then intermediate between those of an ordinary split-phase and a condenser-type motor, using a supplementary condenser for starting.

* *El. World*, March 24 and 31, 1928, pp. 597, 647.

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In a typical case, the best all round performance of a $\frac{1}{2}$ H.P., 1 800 r.p.m., 1-ph., 60-cycle, 110 V condenser motor was obtained when using a condenser of $12\mu\text{f}$, but the characteristics were nearly as good with $10\mu\text{f}$. Fig. 287 shows the characteristics of such a motor; the full load efficiency of 73% and power factor of 0.86 are remarkable in so small a machine.

Figs. 288 and 289 show the usual ranges of efficiency and power factor of split-phase and repulsion-induction motors, together with the corresponding curves for condenser-type motors. By using larger condensers the P.F. of the condenser-type motors can be made unity or leading. In practice the motors of lowest

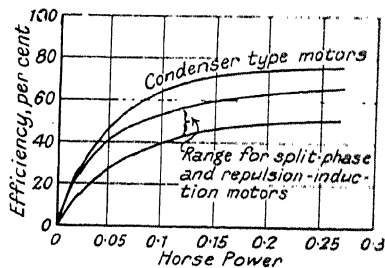


FIG. 288.—Efficiency of 110 V, 60-cycle, 1 800 r.p.m. fractional-H.P. motors on full-load.

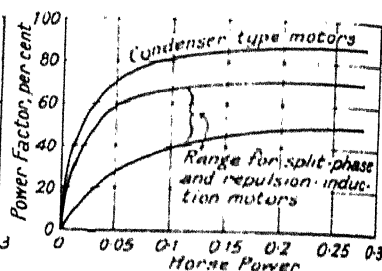


FIG. 289.—Power factor of 110 V, 60-cycle, 1 800 r.p.m. fractional-H.P. motors on full-load.

efficiency have usually the lowest power factor; and it will be seen that the product of efficiency by power factor is from 2 to 2½ times as great for condenser-type motors as for the worst motors of the other two types. In other words, the current consumption of a condenser-type motor may be 50, 40 or even 33% of that for a split-phase or repulsion-induction motor of equal horse power. The supply authority is interested in the total current consumption (varying inversely with the product of efficiency by power factor), while the consumer is interested in the true (Wh) energy consumption (varying inversely with the efficiency).

Table 122 compares the leading characteristics of a condenser motor with the corresponding data for the best repulsion-induction and split-phase motors tested by B. F. Bailey.*

The condenser-type single-phase motor is nearly equal to 2-phase motors in efficiency and superior to them in power factor; it is superior to split-phase 1-phase motors in all respects; and it is inferior to repulsion-induction motors in starting torque per ampere but superior to them in pull-in torque. The motor itself costs about the same as the split-phase machine, to which must be added the cost of the condenser, making the total cost rather more than that of the repulsion-induction machine. On

* *El. World*, March 24 and 31, 1928, pp. 597, 647.

TABLE 122.—*Comparison between Split-Phase, Repulsion-Induction, and Condenser-Type Single-Phase Motors.*Rating: $\frac{1}{4}$ H.P., 1 800 r.p.m., 110 V, 60 cycles in each case.

	Split-Phase Motor.	Repulsion- Induction Motor.	Condenser Motor.
Efficiency, full-load, %	54	64	75
Power factor, full-load, %	60.5	66	86
Apparent efficiency,* full-load, %	32.6	42.2	64.5
Full-load current, amps.	5.15	4.0	2.64
Locked torque, % of full-load torque	186	361	367
Locked current, amps.	31.4	10.8	16.2
Starting efficiency,† %	10.4	58.6	38.3
Pull-out torque, % of full-load torque	217	235	225

* Apparent efficiency : : actual efficiency % \times power factor % / 100.† Starting efficiency = 0.142 (torque, lb.-ft. \times synchronous r.p.m.) / volt-amperes.

the other hand, there are the superior performance and the quieter running (due to 2-phase operation).

691. Parkinson 'Tork' Single-Phase Induction Motor.—

This motor is characterised by its high starting torque per ampere, obtained by means of a pole-changing stator and a rotor which has high effective resistance when the stator is connected to produce the larger number of poles for starting. During normal running, with the lower number of stator poles, the rotor has a low effective resistance. The stator winding is in four sections with four leads to a three-position starting switch and resistance for small motors; a more elaborate starter and an auto-transformer are used with larger machines. As explained later, the function of the starter is: (1) to connect the stator winding to produce an increased number of poles, while using part of it as a starting winding to set up a rotating field; (2) to disconnect the phase-splitting resistance used during the starting period, and to re-connect the stator winding so that the whole of it is used for normal running with a reduced number of poles. According to the value of the phase-splitting resistance, the motor is capable of developing from half full-load torque at starting with $1\frac{1}{2}$ times full-load current, up to from $\frac{1}{4}$ to 1 times full-load torque with twice full-load current; these figures correspond to about three times the torque per ampere of an ordinary squirrel-cage single-phase induction motor, and about twice that of a slip-ring machine.

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The rotor of the 'Tork' motor closely resembles that of a squirrel-cage motor with bare conductors. The latter are connected at one end by a short-circuiting ring, as usual; but, at the other end, special connectors are used between individual bars (see Fig. 290). The distribution of rotor currents is such that a number of these connectors are in series during starting, thus acting as high-resistance end rings. In the larger machines, a wound rotor is used, with slip-rings and external resistances, but no switching is required in the rotor circuit, the rotor currents being diverted electrically from the high-resistance to the low-resistance path when the number of poles in the stator is changed. In order to

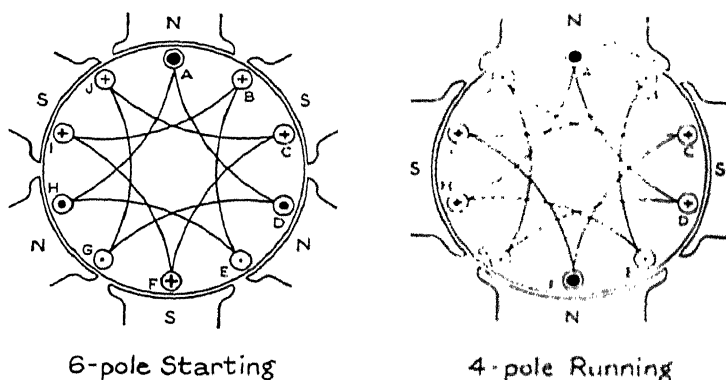


FIG. 290.—Distribution of rotor currents in 'Tork' motor during starting and running.

reverse the motor, it is only necessary to interchange two of the four leads between stator and starter.

The action of the 'Tork' motor may be explained by reference to Figs. 290 and 291.* The first of these shows a 10-bar squirrel-cage rotor (more bars are used in practice) with end connections between fourth bars shown; the stator winding is connected to produce six poles for starting and four poles for running. Consider the moment during starting when the bar *A* is carrying maximum current from back to front as indicated by a large dot (representing the point of an approaching arrow). At this moment, the bars *D* and *H* connected to *A* are carrying current in the same direction though rather less in amount, these bars not being under the centres of their north poles *N*. In order to find a return path from the front to the back of the rotor the current from *A* will have to flow through the

* Reproduced from a detailed description and analysis of the motor in *The Electrician*, July 17 and 24, 1925, pp. 59, 92.

connectors *AD*, *DG*, *GJ*, *JC*, *CF*, and through the connectors *AH*, *HE*, *EB*, *BI*, *IF*. Currents from the other bars marked with dots (approaching arrows) follow equally circuitous routes to bars marked with crosses (representing the tails of receding arrows), i.e. the currents in the bars have to flow through a number of end connections in series so that we have, in effect, a high-resistance rotor during the starting period. When running normally, however, with the stator winding in four-pole connection, the current from bar *A* can return *via* bars *D* and *H* after flowing through single end connections, and similarly in the case of other bars; the rotor circuit is therefore of low resistance as in an ordinary squirrel-cage machine.

With the 6/4 combination of stator poles for starting and running respectively, the maximum starting torque with 6 poles is approximately $1\frac{1}{2}$ times that with 4 poles for the same current, the number of stator conductors in series being the same in both cases. It would not be possible to obtain proportionately higher maximum starting torque by using an 8/4 combination of stator poles because

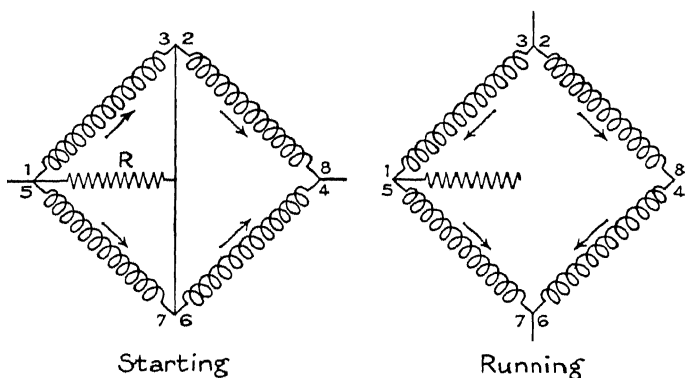


FIG. 291.—Diagrammatic representation of stator connections in 'Tork' motor.

magnetic saturation would then be serious during starting. If it is not desired to take advantage of the increased maximum starting torque obtainable, a given torque can be developed with lower starting current than in an ordinary split-phase machine.

The stator winding of a 'Tork' motor is shown diagrammatically in Fig. 291. The winding is in four similar parts, with *13* and *57* in space quadrature with *28* and *46*. A phase-splitting effect is obtained by connecting a resistance *R* as shown during starting, the mains then being connected to *15* and *84*. For normal running, the resistance *R* is disconnected, and the mains are connected to *32* and *76*. The number of conductors in series remains as before, but the current flow in *31* and *46* has now been reversed. This reversal can be used to change the number of poles and the whole of the winding is used both during starting and during normal running.

Typical data relating to a 3 H.P., 230 V, 50-cycle, single-phase, 4-pole 'Tork' motor are given in Table 123.

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TABLE 123.—*Data Relating to 'Tock' Single Phase Induction Motor.*

Rating 3 H.P., 1 450 r.p.m., 230 V., 50 cycles.

Load.		Speed R.P.M.	Efficiency %	Power Factor.		Current in Amperes.	
H.P.	Fraction of Full-Load.			Alone	With Con- denser.	Alone.	With Con- denser.
$\frac{3}{4}$		1 490	60	0.56	0.94	7.0	4.0
$1\frac{1}{2}$		1 480	70	0.74	0.94	9.4	7.0
$2\frac{1}{2}$		1 470	72	0.82	0.94	12.2	10.5
3	1	1 455	72.5	0.84	0.94	15.5	14.0
$3\frac{3}{4}$	$1\frac{1}{2}$	1 440	72	0.84	0.93	20.0	17.7

692. Schön-Punga Compensated Single-Phase Induction Motor.—This machine has been developed mainly for traction purposes. It operates at unity power factor at all speeds and also during the starting period; and it has a high overload capacity. These results are obtained by using a double rotor, the auxiliary one being annular in form and running concentrically with the main rotor between the latter and the stator. The single-phase field of any single-phase machine may be regarded as being the resultant of two elliptical fields rotating in opposite directions. One of these fields is the useful component, and the other is not only idle so far as concerns the driving of the machine but actually antagonistic. The antagonistic field is travelling at twice synchronous speed (less slip) with regard to the rotor conductors, in which it therefore induces currents. In an ordinary single-phase induction motor the rotor resistance is sufficient to prevent complete compensation of the antagonistic field by these induced currents. In the Schön-Punga motor, however, the intermediate rotor carries a squirrel-cage winding of very low resistance. This rotor runs light at synchronous speed and has therefore no reaction with the working component of the field, but the currents induced by the antagonistic component compensate the latter almost completely. A D.C. winding on the intermediate rotor provides excitation as in a synchronous motor, thus maintaining unity power factor, notwithstanding the double air gap.

The main rotor is provided with an ordinary 3-phase winding. Single-phase supply at any usual frequency (say 50 cycles/sec.) can

be fed to either the stator or the rotor. When supply is to the stator, the main rotor runs in the same direction as the intermediate rotor, but when the supply is to the rotor the latter and the intermediate rotor run in opposite directions. Reversal is therefore effected simply by interchanging the stator and rotor connections. A number of different speeds (*e.g.* 100, 86·5, 66·5, 46·5 and 37·7 %) can be obtained economically by cascade and pole-changing connections. Regenerative braking at unity P.F. is effected when the locomotive drives the motor at higher than the speed corresponding to the connections in use. The fact that the motor does not require a specially low supply frequency, *e.g.* 16 $\frac{2}{3}$ cycles/sec., is one of its principal advantages.

693. Dual-Frequency Induction Motors.—These are machines which are capable of operating on either of two frequencies. They are essentially pole-changing motors (§ 686), but instead of utilising the variable number of poles to obtain different speeds, the alternative numbers of poles are such that the machine will run at the same speed on either of two different frequencies, *e.g.* at a speed of 1 500 r.p.m. (less slip) when connected as a 4-pole machine on 50-cycle supply or as a 2-pole machine on 25-cycle supply. Since the adoption of 50-cycle as the primary standard of frequency for electricity supply in this country, dual-frequency motors have been adopted in some instances for temporary operation on an existing non-standard frequency pending the conversion of supply to 50 cycles. The special arrangement of windings required involves extra initial expense, and the product of efficiency and power factor may be about 5 % lower than for a single-frequency motor. As a sacrifice of efficiency and power factor penalises the user throughout the life of the motor, it is usually best to employ standard single-frequency machines designed respectively for the existing and standard frequencies. Where such a change-over may be necessary, the first motor should not be purchased until it has been ascertained that it will be possible to obtain a standard-frequency machine of equal output and speed, and the same leading dimensions (diameter of shaft, height of centres, arrangement of fixing bolts, etc.).

694. Cascade and Variable-Speed Sets.—Cascade (or concatenated) arrangements of induction motors are used to obtain two for more definite speeds. Two motors are coupled mechanically together and the wound rotor of one machine is connected to the

stator winding of the second. According to whether the connections are such that the motors tend to run in the same or in opposite directions, the speed of the coupled motors is determined by the sum or the difference of the number of poles in each. Speeds lower than each of these two values can be obtained by inserting variable resistance in series with the wound rotor of the second motor. If the numbers of *pairs* of poles in the two motors are p_1 , p_2 , the synchronous speed of the combination on a supply of frequency f cycles/sec. is $60f/(p_1 + p_2)$ with *direct* cascading, i.e. with the motors tending to run in the same direction; and $60f/(p_1 - p_2)$ with *differential* cascading, the motors then tending to run in opposite directions. Further speeds may be obtained by using pole-changing windings, but the complication is then a serious consideration.

The Hunt 'single-field cascade motor' is electrically and magnetically identical with a cascade combination of two separate machines, but the two stator and rotor windings of the latter are replaced by single windings and there is only one magnetic core. The cost is thus reduced, and the efficiency and P.F. are improved. The stator winding connected to the supply produces say 8 poles and induces currents in the rotor windings, which are so arranged as to produce both an 8-pole and a 4-pole effect. The 8-pole field of the rotor corresponds to the main field of the stator, and the 4-pole rotor-field rotates in the opposite direction and induces currents in the stator winding. The latter is so connected that the main and slip-frequency currents can circulate independently. By using various arrangements of windings, three or four different speeds can be obtained efficiently from a single machine (usually within the range 3 : 1). Intermediate speeds can be obtained by rheostatic control.*

Variable-speed sets consisting of a wound rotor induction motor and an auxiliary A.C. commutator motor or frequency-changer make possible efficient operation over a wide range of speeds and at higher P.F. than that of an induction motor alone. Instead of the 'slip energy' of the main rotor being dissipated in external resistance in order to regulate the speed of the machine, this energy is fed to the auxiliary machine. The output of the latter, amount-

* For a detailed treatment of the Hunt motor, see *Jour. I.E.E.*, Vol. 52, p. 406.

ing to about 90 % of the slip-energy input, may be added to that of the main motor by coupling the machines mechanically, or it may be returned to the mains *via* an asynchronous generator driven by the auxiliary motor (§ 728). The magnitude of the back-E.M.F. of the auxiliary motor determines the slip and therefore the speed of the main motor; and the P.F. of the latter can be improved by advancing the phase of the auxiliary machine's E.M.F. The size of the auxiliary motor is determined by the percentage slip, s , which it is required to produce in the main motor, but the same auxiliary motor can vary the speed from s % above to s % below synchronism, thus giving twice the speed range, if the synchronous speed is at the middle of the range.

The uses of cascade and variable-speed sets are restricted in practice to high-power drives, such as rolling mills, colliery winders, large pumps, and so on. Further particulars are given in §§ 727, 728; and the P.F.-load and other characteristics of typical asynchronous motors with self-excited and separately-excited exciters are given in Table 124, § 695, and Figs. 292 (*d*) and (*e*), the dotted curves in the latter case referring to increased values of D.C. excitation in the main machine.

695. Power-Factor Correction for Induction Motors. Comparison between Types of Motors.—Typical values of power factor for induction motors are given in § 681, and conditions which influence the actual value are noted. The P.F. of a mixed installation of induction motors on variable load rarely exceeds 0.7 and often falls to 0.4. The need for P.F. improvement in such cases is urgent; see Chapter 5, Vol. 1, which deals fully with the methods, calculations, and economics of P.F. correction. In many instances, special types of induction motors operating at high or leading P.F. can be used to advantage, *e.g.* auto-compensated induction motors (§ 688), condenser-type motors (§ 690), or synchronous-asynchronous motors (§ 696).

Where ordinary induction motors are already in use and it is desired to improve the P.F. any of the methods described in § 160, Vol. 1 may be used. Static condensers are very convenient for use with motors of small and medium H.P., and they offer the advantage that the P.F. of the combination can easily be made 0.9 or higher at all loads from about $\frac{1}{2}$ -load upwards. For average 440 V, 50-cycle, 3-phase motors the condenser capacity required to raise the P.F. to 0.95 on full-load ranges from about 30 μ F for

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a 5 H.P. motor to 50 μ F for a 10 H.P., 75 μ F for a 25 H.P., and 110 μ F for a 50 H.P. motor, approximately.

For large motors, 150 H.P. or over, the use of electromagnetic phase advancers (§ 160 *d*, Vol. I), or various combinations of an induction motor with an auxiliary commutator motor (§ 694), should be considered. A series-type phase advancer is subject to the draw-back that the correcting or phase-advancing effect decreases with the load on the motor and is almost negligible at and near no-load, just when it is most needed. The Scherbius shunt-wound phase-advancer is not subject to this defect.* When contemplating the adoption of any P.F.-correcting device, it is important to examine its effect at all values of load on the main motor.

Fig. 292 and Table 124 are particularly interesting in that they compare the characteristics of a number of different types of motors as made by the same manufacturer (Siemens-Schuckert). All of these machines are capable of improving the average P.F. of a consumer's load by operating at unity P.F. at full-load and, in most cases, by operating at a leading P.F. on fractional loads, thus exerting an actual phase-correcting effect. Fig. 292 shows the connections of each machine in diagrammatic form, and the

TABLE 124.—*Range of Capacity, Maximum Voltage, and Torque Values for Motors shown in Fig. 292. (SIEMENS-SCHUCKERT.)*

	(a).	(b).	(c).	(d).	(e).	(f).	(g).
	Synchron- ous Motor with Damping Winding.	Synchron- ous Motor with Starting Winding.	Synchron- ous-Asyn- chronous Motor.	Asyn- chronous Motor with Self- Excited 3-ph. Exciter.	Asynchron- ous Motor with Separately Excited Exciter.	Osborn Motor.	Hey- land Motor.
Range of kW	2½-20 000	20-700	40-2 000	40-1 500	100-10 000	7½-40	1½-5
Max. voltage	10 000	10 000	10 000	10 000	10 000	500	500
Starting torque†	80 %	100-180 %	180-200 %	200 %	200 %	200 %	180 %
Synchronous pull- out torque†	180 %	170 %	150 %				
Asynchronous pull-out torque.†		180-200 %	200 %	250 %	250 %	250 %	250 %

* For details see *Jour. I.E.E.*, Vol. 67, p. 681.

† Per cent. of full-load torque.

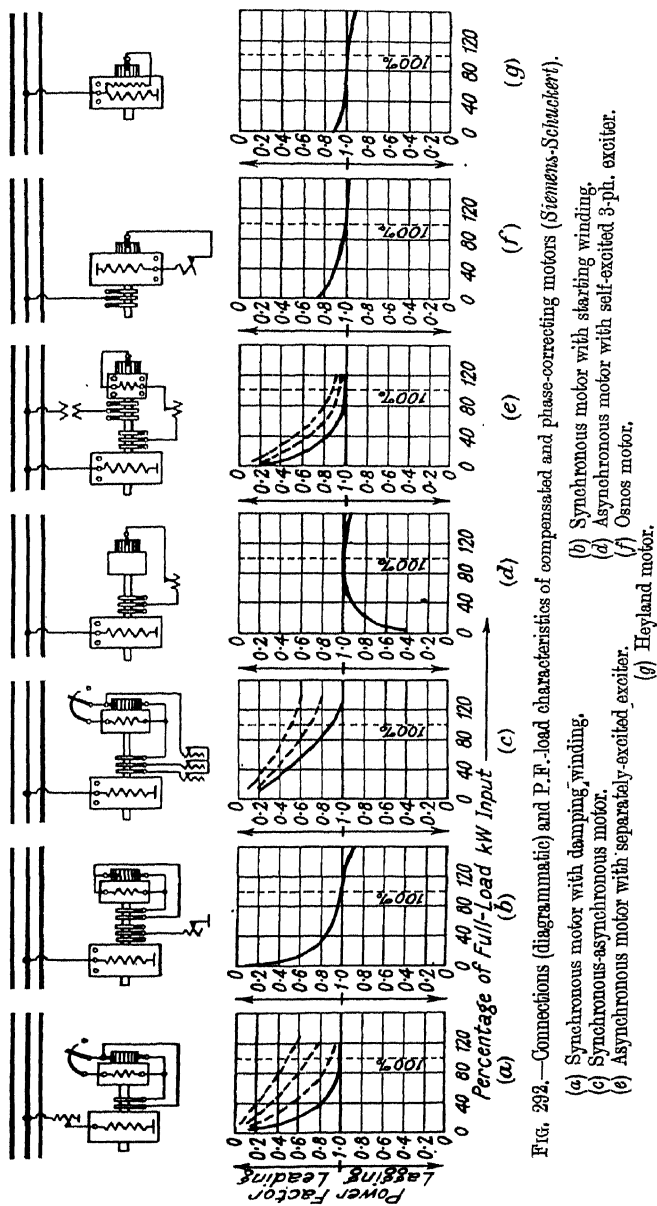


FIG. 292.—Connections (diagrammatic) and P.F. load characteristics of compensated and phase-correcting motors (Siemens-Schuckert).

relation between the P.F. of the motor and the kW consumption as a percentage of the full-load value : whilst Table 124 shows the range of capacities in which each motor is available, the maximum voltage, and the torque characteristics of the machine. The dotted curves in Fig. 292 (a), (c) and (e) relate to higher values of D.C. excitation.

696. Synchronous Asynchronous (or Synchronous-Induction) Motors.—These machines are essentially slip-ring induction motors with a rather longer air gap than an ordinary induction motor, and with provision for D.C. excitation during normal running. The motor starts as a slip-ring induction motor, with a higher starting torque than can be obtained from a salient-pole synchronous motor (§ 679), but normally operates as a synchronous motor with a higher P.F. (unity or leading) than can be obtained from an induction motor. If the load becomes too heavy to be driven synchronously, the motor drops back into asynchronous operation and continues to run thus until the safe limit of heating or the stalling torque of the machine as an induction motor is reached, whichever occurs first. P.F. correction can be effected during the whole time the motor is running synchronously (§ 160 (c), Vol. 1, and § 679). The size and price are about the same when the machine is designed for operation at 0.9 leading P.F. on full-load as when it is designed for unity P.F., so that it is obviously best to choose the 0.9 P.F. design. A P.F. of 0.7 leading (at full-load) can be obtained, but the motor is then considerably larger and more expensive. The P.F. load and other characteristics of a typical synchronous-asynchronous motor are given in Table 124 and Fig. 292 (e), § 695, the dotted curves relating to increased values of D.C. excitation.

The size and cost of the synchronous-asynchronous motor are rather greater than those of a plain induction motor of equal rating, and the efficiency of the former is generally 0.5 to 1.0 % lower, but these facts are more than compensated by the advantage of P.F. correction where power is generated privately or purchased under a tariff taking P.F. into account.

In the self-starting synchronous motor with salient poles, a squirrel-cage or phase-wound winding in the pole shoes is used for starting, and separate windings on the pole cores are used for the D.C. excitation. In the synchronous-induction motor, however, a cylindrical rotor is used with a 2-phase or 3-phase winding

in slots. This winding is used during the starting period and also for D.C. excitation. Direct current for the field circuit is usually obtained from an exciter dynamo direct-coupled to the motor, or chain-driven from the motor shaft if the speed of the latter is low. The exciter E.M.F. is usually between 30 and 60 V, and a rheostat in the exciter field circuit enables the excitation of the motor to be varied at will. At the moment of starting, the A.C. voltage across the slip rings may be as high as 1 000 or 2 000 V.

If the secondary (usually the rotor) windings be 3-phase, they are excited for synchronous operation by passing D.C. through one phase to the star point and thence through the other two phases in parallel (see Fig. 293).

Alternatively, the rotor may be provided with a 2-phase, 3-wire winding, the neutral point of which is connected to one of the exciter brushes, while the outer terminals are connected to two poles of a 3-pole liquid starter; the third (earthed neutral) pole of the latter is connected to the second brush of the exciter. The exciter is permanently in circuit and is not affected by the high voltage between the motor slip rings at starting, because it is connected to the earthed neutral. The advantage of this arrangement, which is used in the Crompton-Parkinson 'auto-synchronous' motor (see Plate facing, p. 229, Vol. 1), is that the D.C. field current divides equally between the 2-phase windings in parallel. If a 3-phase winding be used, the windings cannot be balanced for both starting and running conditions. If the windings be balanced during starting, one phase carries twice as much current as either of the other two during normal running and is thus subjected to four times the heatings. On the other hand, if balance is to be obtained when the excitation current is flowing, one phase of the rotor winding must be split and, as a result, the windings are out

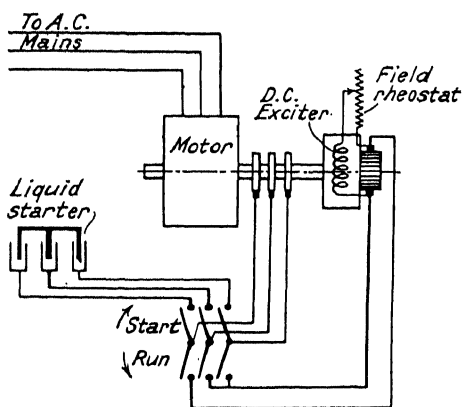


FIG. 293.—Connections of synchronous-asynchronous motor.

The exciter is permanently in circuit and is not affected by the high voltage between the motor slip rings at starting, because it is connected to the earthed neutral. The advantage of this arrangement, which is used in the Crompton-Parkinson 'auto-synchronous' motor (see Plate facing, p. 229, Vol. 1), is that the D.C. field current divides equally between the 2-phase windings in parallel. If a 3-phase winding be used, the windings cannot be balanced for both starting and running conditions. If the windings be balanced during starting, one phase carries twice as much current as either of the other two during normal running and is thus subjected to four times the heatings. On the other hand, if balance is to be obtained when the excitation current is flowing, one phase of the rotor winding must be split and, as a result, the windings are out

of balance during the starting period; the starting characteristics are therefore impaired.

The distinctive features of the self-exciting Fynn-Weichsel synchronous-asynchronous motor are described in § 697.

The synchronous-asynchronous motor is capable of developing a starting torque equal to 2 to $2\frac{1}{2}$ times the full-load torque, as compared with about half the full-load torque in the case of a salient-pole synchronous motor with squirrel-cage starting winding. It develops a 'pull-in' or synchronising torque equal to $1\frac{1}{2}$ to $1\frac{1}{2}$ times full-load torque; and pulls out of synchronism at about 1.6, 1.75 or 2.0 times full-load torque according as it is excited for a P.F. (at full-load) of 1.0, 0.9 leading or 0.8 leading. Apart from the effect of the leading P.F., in correcting the lagging P.F. of induction motors on the same network, it is worth while to employ the higher D.C. excitation because of the higher pull-out torque thus secured. If the motor be operated at unity P.F. it may be pulled out of step rather frequently by overloads, particularly if the supply voltage be low, and, under these conditions, there may be some difficulty in pulling back into synchronism.

Summary of Characteristics and Applications. The synchronous-asynchronous motor combines the characteristics of the synchronous and induction motors to the extent that it combines the self-starting property and relatively high starting-torque of the induction motor with the constant-speed and unity or leading P.F. of the synchronous motor when running normally on load. In addition, the motor can be so designed that it will continue to run as an induction motor should it be pulled out of synchronism by an overload, and will subsequently revert automatically to synchronous operation directly the load decreases sufficiently to enable it to pull into step. The synchronous-asynchronous motor is now used in many applications which would formerly have required the use of an induction motor; and, as regards ease of starting and stability of operation, it is preferable to the plain synchronous motor. Typical applications are to compressors, mine and other large fans, pumps, generators, lineshafts, and machinery which has normally to be driven at constant speed but is subject to intermittent overloads when a slight decrease of speed is permissible (*e.g.* grinders). Usual sizes range from 50 to 1 500 H.P. or even 5 000 H.P., with direct connection of the stator to 2 or 3-phase supply at any voltage up to 11 000 V or so.

The use of synchronous-asynchronous motors instead of ordinary slip-ring induction motors should always be considered, particularly where low speed machines are concerned. On the other hand, the alternative of using a slip-ring induction motor in conjunction with a phase advancer (§ 160, Vol. 1, and § 694) should also be considered; this is sometimes a cheaper, more efficient and more flexible method.

697. Fynn-Weichsel Synchronous-Asynchronous Motor.

—The Fynn-Weichsel motor runs normally as a synchronous machine, at leading P.F., but during starting and on heavy overload it runs as a slip-ring asynchronous motor. It is self-synchronising when starting or on the removal of the heavy overload, as the case may be, and it requires no external supply of D.C. for its excitation. It thus combines the absolute constancy of speed and the P.F.-correcting ability of the synchronous motor at all loads up to from 1.5 to 1.9 times full-load, with the good starting characteristics and high overload capacity of a slip-ring induction motor. Starting as a slip-ring induction motor it develops about $1\frac{1}{2}$ times full-load torque with from $1\frac{1}{2}$ to 2 times full-load current; it is capable of pulling into synchronism against $1\frac{1}{2}$ to 2 times full-load; and its efficiency increases steadily from about 82 % at $\frac{1}{2}$ -load to 88 % at full-load, and 89 % at $1\frac{1}{2}$ to 2 times full-load, thereafter falling to about 85 % when the machine pulls out of synchronism, and reaching about 75 % at three times full-load, when the motor is on the point of being stalled by overload (see Fig. 294). It is usually arranged that the P.F. of the motor is unity at the maximum load which can be carried synchronously; it is then about 0.9 *leading* at full-load, and about 0.6 *leading* at no-load. In other words, the characteristics of the machine are those of a synchronous motor up to $1\frac{1}{2}$ to 2 times full-load, and those of an induction motor during starting and from $1\frac{1}{2}$ or 2 to 3 times full-load. An important point is that the motor re-synchronises automatically when the overload falls to less than $1\frac{1}{2}$ to 2 times full-load. Self-excitation for synchronous operation is provided by an auxiliary winding connected to a commutator on the rotor. By using one or more synchronous-asynchronous motors in conjunction with ordinary induction motors, the resultant P.F. of the whole installation can be kept at or near unity over a wide range of load (§ 160 (c), Vol. 1); moreover, the phase-correction can be effected almost as near to the sources of lagging

P.F. (the ordinary induction motors) as though static condensers were used (§ 160 (a), Vol. 1).

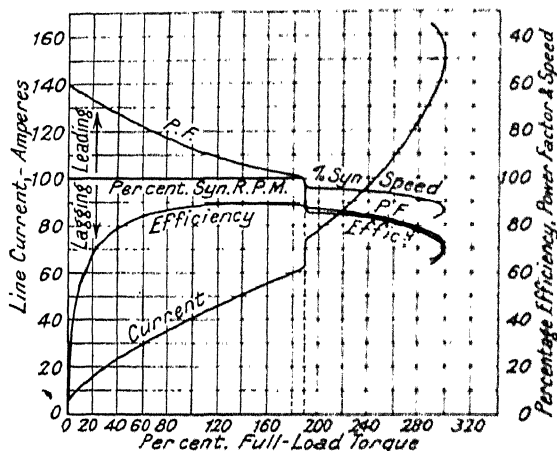


FIG. 294.—Typical characteristic curves of Fynn Weichsel motor.

The theory and construction of the Fynn-Weichsel motor have been described in a number of papers; * the following are the principal features:—

In general construction, the machine resembles an induction motor with the secondary winding on the stator, and the primary

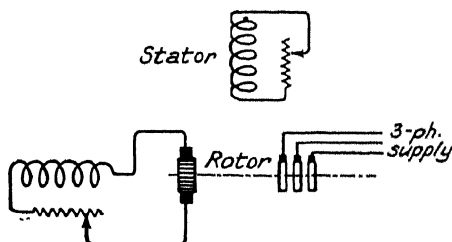


FIG. 295.—Fynn-Weichsel synchronous-asynchronous motor.

on the rotor supplied through slip rings. The stator slots contain two independent windings displaced 90° electrically from each other. Variable resistance can be placed in service with each of these windings for starting (as in the case of the rotor circuit of an ordinary slip-ring induction motor), and one of the stator windings is

connected in series with a small D.C. winding at the bottom of the

* Notably by H. Weichsel, *Jour. Amer. I.E.E.*, April, 1925, and *Jour. Franklin Inst.*, May, 1925.

rotor slots, through brushes and a commutator as shown diagrammatically in Fig. 295.

The A.C. supply to the rotor produces a field rotating with regard to the rotor winding. The rotor turns in the opposite direction to this rotating field and, at synchronism, the latter is stationary in space, though still rotating at synchronous speed with regard to the rotor.

The voltage at the commutator brushes depends only on the design of the winding connected to the commutator and on the velocity of the rotating field with regard to this winding; this velocity is not affected by the rotation of the rotor, hence the voltage at the commutator brushes is constant. The frequency of the E.M.F. available at the commutator brushes equals the frequency of the 'slip' current in the stator windings, and the phase of the commutator E.M.F. and the stator E.M.F. can be made the same by adjusting the position of the brush axis on the commutator. In other words, connecting the machine as in Fig. 295 results in adding an E.M.F., of the same frequency and phase, to the slip-E.M.F. already acting in the stator winding. This causes the machine to run at a speed higher than that at which it would operate without the injected E.M.F.

For example, if the induced slip-E.M.F. in the secondary is 6 V and we inject 2 V from the commutator brushes, the total E.M.F. is 8 V, and the secondary current would be $8/6$ times its normal value if the slip were kept constant. Actually, the slip will decrease in about the ratio $6/8$, so that the current remains at the value required by the load on the motor. As already explained, the injected voltage remains constant, but the slip-E.M.F. decreases as the machine approaches synchronism, hence the speed-raising effect of the injected E.M.F. is cumulative. Instead of the machine tending to remain at the induction motor speed with, say, 5 % slip, it is raised automatically and progressively above this speed after all the starting resistance has been removed from the stator circuits, and pulls into synchronism with a powerful torque and moderate current consumption. At synchronism there is no slip-E.M.F. in the secondary windings; but the E.M.F. at the commutator brushes retains its full value and is now of zero frequency, *i.e.* it is a direct current E.M.F. In other words, the auxiliary winding on the rotor which ensures automatic synchronisation now excites the field for operation as a synchronous motor.

Fig. 296 * shows dotted the speed-torque curves of a Fynn-Weichsel motor operating as an ordinary induction motor with no external resistance in the secondary (curve 1), with sufficient secondary resistance to give maximum starting torque (curve 2), and with an intermediate value of secondary resistance as required to give a starting torque equal to $1\frac{1}{2}$ times full-load torque (curve 3). Curves 4, 5, and 6 relate to the same machine and the same values of secondary resistance, but with an injected E.M.F. from the commutator brushes added to the induced slip-E.M.F. in the secondary. A higher speed is now obtained for given torque, and a higher torque for given speed. The additional torque, due to

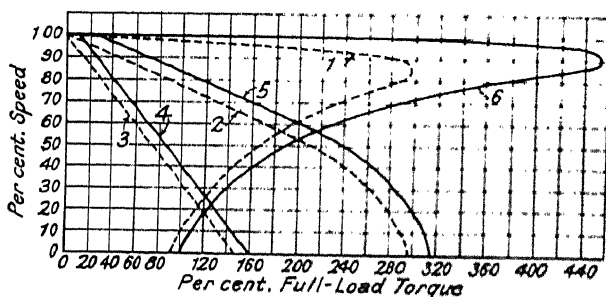


Fig. 296.—Speed-torque curves of Fynn-Weichsel motor.

the injected current, pulsates with the frequency of the latter until synchronism is reached and is then constant.

Fig. 294 shows typical characteristic curves of a 15 H.P., 60-cycle, 1 800 r.p.m., 220 V, 3-phase Fynn-Weichsel motor over its complete range of operation. Motors of this type are built in sizes up to 200 H.P., or larger if required. They are applicable to any constant speed drive, and are particularly useful for driving grinders and other machines subject to heavy overloads, the motor then dropping into asynchronous operation, but reverting to synchronism directly the overload is reduced to from $1\frac{1}{2}$ to 2 times full-load.

The 'Tru-Watt' or Crompton-Burge motor (Messrs. Crompton Parkinson, Ltd.) is of the same type as the Fynn-Weichsel machine. The Authors are informed that it originated with the patent 15,523

* H. Weichsel, *Jour. Franklin Inst.*, May, 1925.

(1913) but was not put on the market until some years later, when the power factor problem became acute.

698. Super-Synchronous Motors.—The term super-synchronous motor is really applicable to any A.C. motor which is capable of running at higher than the synchronous speed corresponding to the frequency of the supply and the number of poles in the motor. Usually, however, the term is restricted to other than commutator motors.

The synchronous speed of a motor having p pairs of poles, running on a supply of frequency f cycles per sec., is $n = 60f/p$ r.p.m. (§ 135, Vol. 1), hence the highest possible speed for a synchronous motor on 50-cycle supply is 60×50 or 3 000 r.p.m., this necessitating a 2-pole construction. There are, however, many machines (*e.g.* wood-working machines, small grinding wheels, and centrifuges) which need to be driven at higher speeds up to 8 000 or 10 000 r.p.m., and for such purposes it is necessary to use a super-synchronous motor if the advantages of direct coupling are to be retained. A frequency changer converting the supply to 100 or 150 cycles per sec. would raise the speed of 2-pole synchronous motors to 6 000 or 9 000 r.p.m. respectively, but the cost of the frequency changer and separate cables for the high frequency supply is seldom justifiable.*

The '*double-field*' or '*double-fed*' synchronous motor runs at twice the synchronous speed, *i.e.* at 6 000 r.p.m. in the case of a 2-pole machine. The 3-phase windings on the stator and rotor are both connected to the supply but in opposite phase sequence; a rotating field is thus produced in each, but the directions of rotation of the fields, with regard to the windings which produce them, are opposite. Suppose that the stator field rotates at angular speed $+\omega$; then the rotor field rotates at angular speed $-\omega$ with regard to the rotor winding. If now the rotor itself be brought up to double synchronous speed $+2\omega$ (this must be done mechanically or by means of an auxiliary commutator), the net speed of the rotor field in space will be $2\omega - \omega = \omega$. This is the same as the speed of the stator field, hence the two fields will continue to rotate in

* A simple type of frequency changer, which can be used to supply a few small motors, consists of an induction motor with a wound rotor driven mechanically at synchronous speed in the opposite direction from that in which it would rotate if the machine were running as a motor. Under such conditions, current at twice the frequency of the main supply can be taken from the slip rings of the rotor.

synchronism. In other words, the motor will run synchronously but at twice synchronous speed. The only practical objection to this machine is the difficulty of bringing the rotor up to twice synchronous speed when starting. This difficulty is overcome in the Pistoye triple synchronous motor described later in this paragraph.

The double stator-double rotor induction motor * operates on a similar principle. Being an induction motor it cannot reach twice the synchronous speed but only twice the synchronous speed *minus* the sum of the slips of the respective rotors. Between the main stator and the main rotor there is an annular rotor carrying a squirrel cage winding on the outside and a second stator winding on the inside (see Fig. 297). This auxiliary rotor is mounted on bearings concentric with the main bearings. If both stators have 2-pole windings, connected to a 50-cycle supply, the intermediate rotor will rotate at 3 000 r.p.m. (less slip) relatively to the fixed stator S_1 , and the main rotor will rotate at 3 000 r.p.m. (less slip)

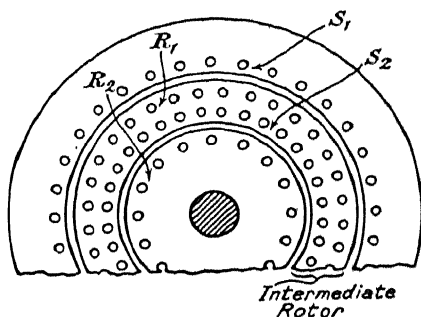


FIG. 297.—Double stator-double rotor induction motor.

with regard to the intermediate stator S_2 ; but, as the latter is already rotating at 3 000 r.p.m. (less slip), the actual speed of the rotor R_2 will be 6 000 r.p.m. (less the sum of the two slips). The machine is a mechanical combination of two motors which are electrically distinct; the stator of the second machine is rotated by the first motor, hence the second

rotor runs at a speed which equals the sum of the speeds of the rotors in two mechanically independent motors of the same electrical characteristics. Theoretically, any number of electrically distinct motors could be combined mechanically in this way giving 3, 4, 5, etc., times the synchronous speed of a single motor, but it is almost impossible in practice to have more than two concentric rotors.

* Not to be confused with the double-rotor, single-stator machine (§ 685) used to obtain higher starting torque.

The construction of the intermediate rotor, Fig. 297, is simplified, and the action of the motor is unaffected, by interchanging the stator and rotor windings S_2 and R_2 , so that the intermediate rotor carries only two squirrel-cage windings.

An interesting feature of the motor shown in Fig. 297 is the possibility of obtaining different speeds by varying the number of poles in S_1 and S_2 . The synchronous speed corresponding to a 2-pole stator S_1 and a single rotor is 3 000 r.p.m. on 50-cycle supply. By using a double rotor with a 2-pole winding S_2 , the synchronous speed of R_2 is 6 000 r.p.m.; but if S_2 has four poles, the speed of R_2 with regard to S_2 is 1 500 r.p.m. and the actual speed of R_2 is $3\,000 + 1\,500 = 4\,500$ r.p.m. In general, on a supply frequency of f cycles per sec., with p_1 pairs of poles in S_1 and p_2 pairs of poles in S_2 , the speed of R_2 is $\frac{60f}{p_1} + \frac{60f}{p_2}$ r.p.m. (less the sum of the slips), the phase rotation being the same in S_1 and S_2 ; if the phase rotation be opposite in the two stators the speed of R_2 is the *difference* between the above two terms. If the intermediate rotor be held stationary, by a brake, the speed of R_2 is that of a single-rotor machine with stator winding S_1 .

Motors of this type, giving higher speeds than can be obtained with single stator and rotor machines on the same frequency of supply, are used to drive wood planing and thicknessing machines, moulding machines, and other machines requiring a high speed of spindle rotation.

Suppose, for example, that the outer stator is wound with four poles and the inner stator (on the outer rotor) with two poles. With 50-cycle supply to the stators, the outer rotor will run at 1 500 r.p.m. (less slip) with regard to the outer stator, and the inner rotor will run at 3 000 r.p.m. (less slip) with regard to the outer rotor and therefore at 4 500 r.p.m. (less slip) with regard to the outer stator, assuming that the two rotors run in the same direction. If it be arranged that the outer stator winding can be re-connected as a 2-pole winding, the speed of the inner rotor can be raised to 6 000 r.p.m. (less slip). Finally, by arranging to lock the outer to the inner rotor, and supplying only the outer stator, speeds of 3 000 and 1 500 r.p.m. (less slip) are obtained with the stator connected 2-pole and 4-pole respectively. In other words, using the double stator and rotor motor with a 4/2 pole-changing outer stator, a 2-pole inner stator and provision for locking the outer to the inner rotor, speeds of 6 000, 4 500, 3 000, and 1 500 r.p.m. (less slip in each case) can be obtained on 50-cycle supply.

Many intermediate speeds can be obtained, over a wide total range, by combining the principles of pole-changing, phase reversal, and mechanical locking of one rotor. Thus Table 125 shows the

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TABLE 125.—*Speeds of Double-Rotor, Pole-Changing, Induction Motor.*

Combination No. (see Fig. 298).	No. of Poles on		Phase Rotation of Field S_1 with regard to Field S_2 .	Synchronous Speed* of R_2 (50 Cycle Supply).
	Stator S_1 .	Stator S_2 .		
1	12	2	Same	3 500
2	16	2	"	3 375
3	24	2	"	3 250
4	32	2	"	3 127
5	R_1 stopped	2		3 000
6	32	2	Reversed	2 813
7	24	2	"	2 750
8	16	2	"	2 625
9	12	2	"	2 500
10	12	4	Same	2 000
11	16	4	"	1 875
12	24	4	"	1 750
13	32	4	"	1 627
14	R_1 stopped	4		1 500
15	32	4	Reversed	1 313
16	24	4	"	1 250
17	16	4	"	1 125
18	12	4	"	1 000

* Actual speed less by the total amount of slip.

speeds obtainable in this way in an Oerlikon motor rated at 80 H.P. at 1 000 r.p.m. and 300 H.P. at 3 500 r.p.m.* It is claimed that

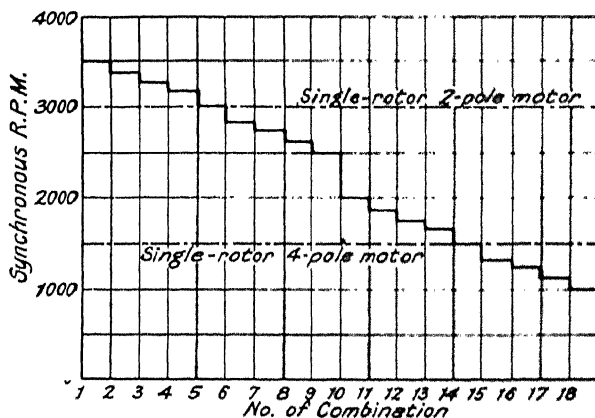


FIG. 298. Speeds of double-rotor pole-changing induction motor (see Table 125).

* Vide 'Super-Synchronous Motors,' by C. W. Oliver, *Power Engineer*, Vol. 28, p. 269.

the P.F. and efficiency are 'very satisfactory' throughout at all speeds, the range and fineness of gradation of which are remarkable for an A.C. induction motor. As shown by Fig. 298 the speed steps are reasonably uniform except between combinations 9 and 10 where there is a change of 500 r.p.m.

The Pistoye *triple-synchronous motor* is essentially a combination of the double-field (or double-fed) synchronous and double stator-double rotor induction motors described above. This machine may be represented diagrammatically by Fig. 297, but $S_1 R_1$ are

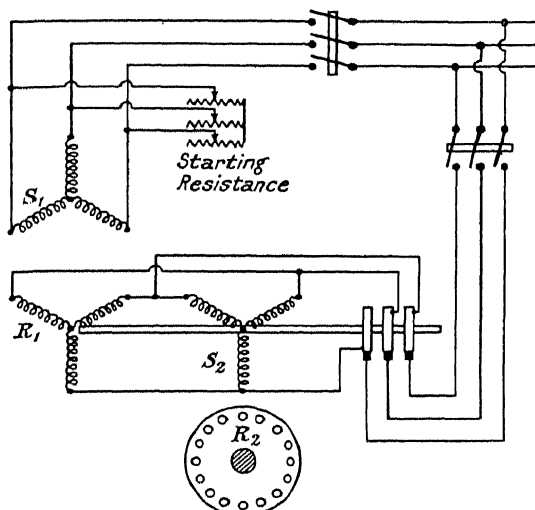


FIG. 299.—Connections of triple-synchronous speed motor.

now the similar 3-phase windings of a double-field synchronous motor, hence, when the motor is in service, the intermediate rotor runs at twice synchronous speed. The windings $S_2 R_2$ are those of an ordinary induction motor, so that R_2 runs at synchronous speed (less slip) with regard to S_2 and therefore at an actual speed of three times the synchronous speed (less the slip between S_2 and R_2). As already noted, the difficulty with the double-field synchronous motor is to bring the rotor up to twice synchronous speed when starting, but this is effected quite easily in the Pistoye motor.

Referring to Fig. 299 (Olliver, *loc. cit.*), the stages of starting are as follows:—

(1) The intermediate rotor is fed from the mains, and the stator S_1 is connected to starting resistances as shown, these resistances being gradually cut out. The combination S_1R_1 accelerates as an inverted induction motor, and the main rotor R_2 comes up to twice synchronous speed (less slip, see explanation of double stator-double rotor induction motor above).

(2) When the intermediate rotor, carrying R_1 and S_2 , has reached synchronous speed (less slip), two of the slip-ring connections are reversed and S_1 is open-circuited. There is now no torque between R_1 and S_1 (because S_1 is open circuited); and, the field of S_2 being reversed, there is a braking torque between S_2 and R_2 , tending to stop R_2 . The inertia of R_2 is, however, much greater than that of the intermediate rotor (which is now running light and free), hence the torque between S_2 and R_2 accelerates the intermediate rotor and brings it up to twice synchronous speed.

(3) The intermediate rotor running at or near synchronous speed, the stator S_1 is connected to the mains, whereupon R_1 pulls into synchronism and the combination S_1R_1 runs as a double-field synchronous motor. Simultaneously, the original phase connections to the slip rings are restored.

(4) With the intermediate rotor now running steadily at twice synchronous speed, the main rotor will accelerate until it reaches three times synchronous speed (less slip).

It is possible to devise combinations giving yet higher speeds, but apart from the cost and complexity of construction, the mechanical stresses on the rotors become serious. The alternative of a geared-up drive from a motor of normal construction should be considered.

699. A.C. Commutator Motors: General. The A.C. commutator motor sacrifices the obvious advantage possessed by induction and synchronous motors, *viz.* absence of commutator and freedom from commutation problems. On the other hand, it is free from the principal restriction of induction and synchronous motors, that of being limited more or less definitely to a synchronous speed. The justification for the commutator lies in the range of speed control which it makes possible without undue complication or sacrifice of efficiency. The highest speed attainable in a synchronous motor (and the speed of an induction motor is lower by the amount of the slip) is $60 f/p$ r.p.m., where f = supply frequency in cycle/sec., and p = number of *pairs* of poles. The highest speed for any synchronous or induction motor on 50-cycle supply is thus 3 000 r.p.m. for a 2-pole machine, 1 500 r.p.m. for a 4-pole machine, and so on, unless one adopts a special super-synchronous combination (§ 698). An A.C. commutator motor, however, is capable of operating at speeds above as well as below synchronism,*

* The 'synchronous speed' of an A.C. commutator motor is equal to that of a synchronous motor having the same number of poles.

and, apart from any inherent variation of speed with load, continuous control of speed over a wide range is obtained by shifting the brushes on the commutator, using either manual gearing or a servo-motor to actuate the brush rocker.

A.C. commutator motors are usually built for either 1-phase or 3-phase operation, with shunt or series characteristics as desired in either case. The terms shunt and series characteristics are used by analogy with the characteristics of D.C. shunt and series motors; the speed of the shunt-type motor is more or less nearly constant at all loads, whereas the speed of the series-type motor decreases very considerably as the load increases.

So many different schemes of connections and operation have been developed for A.C. commutator motors* that it is impossible here to deal with all of them, but the following paragraphs (§§ 700-709) cover the principal types. Certain general constructional features are common to each. In the first place, owing to the fact that the magnetic flux is alternating in all parts of an A.C. commutator motor, the whole of the iron in the magnetic circuit must be laminated. The stator winding may be likened to that of an induction motor, and the rotor winding to that of a D.C. motor. Whereas a D.C. series motor is capable of operating on A.C., subject to certain limitations discussed in § 700, the high reactance offered by the field winding of a D.C. shunt motor to the passage of A.C. makes this type inapplicable to A.C. working; a different arrangement has therefore to be used in order to obtain shunt characteristics in an A.C. commutator motor.

The commutator of an A.C. machine is usually large, compared with that of a D.C. motor, and the arrangement of the brushes depends on the type of motor concerned. In 3-phase machines there are three sets of brushes spaced 120 electrical-degrees† apart. Provision is generally made for shifting the brushes, as a

* In *The A.C. Commutator Motor* (Chapman & Hall), C. W. Olliver tabulates twenty-eight different types of single-phase commutator motors, besides many types of polyphase machines.

† In a 2-pole machine the spacing would be 120 degrees of arc (or geometrical degrees), but in a 4-pole machine the spacing would be 60 degrees of arc, this still being 120 degrees as regards electrical phase. The geometrical angle corresponding to θ 'electrical degrees' = θ /number of pairs of poles in the machine. Conversely, the angular displacement in 'electrical degrees' = geometrical angle or angle of arc \times number of pairs of poles.

whole or in two sets, round the commutator for purposes of speed control.

Wherever brush-shifting A.C. commutator motors of series characteristics are used for variable-speed service, the H.P. of the motor should be as nearly as possible equal to the H.P. demanded by the load. "Overmotoring" in such a case is not only extravagant but also involves unduly large displacement of brushes in order to operate at reduced speed (the speed of the underloaded motor tends to rise owing to the series characteristic of the machine). This wide displacement of the brushes generally involves working on a less stable torque-speed characteristic.

The problem of commutation is much more difficult in A.C. motors than in D.C. machines, mainly owing to the fact that an E.M.F. is induced in the short-circuited turns by the transformer action of the main alternating field, the latter being of the same frequency as the A.C. supply. The magnitude of the induced E.M.F. is lower, the lower the frequency of the supply current, the fewer the number of short-circuited turns, and the lower the density of the inducing field: hence the advantage, from this standpoint, of a low supply frequency, a large commutator with many bars and narrow brushes, and a relatively low number of ampere-turns in the main field. The E.M.F. actually induced in the short-circuited turns may be neutralised by interpoles or by a flux established by short-circuiting auxiliary brushes; and, in view of the relatively weak field, a special winding (or its equivalent) may be used to neutralise the armature reaction. Generally, commutation is excellent at and near synchronous speed, but increasingly liable to give trouble as the speed becomes much above or below synchronism. A low commutator voltage is necessary, seldom exceeding 200 V and often 100 V or less; a special transformer may be needed in order to secure this. The diameter of the commutator necessary for good commutation increases with the supply frequency, and in a 50-cycle motor the diameter of the commutator is often nearly equal to that of the rotor.

In the interests of high P.F., the main field should be as weak as possible, the air gap short, and the supply frequency low. These features of design are also desirable in the interests of good commutation, as noted above.

The efficiency of an A.C. commutator motor is usually slightly

lower than that of the corresponding induction motor at the normal speed of the latter, but materially higher than that of the induction motor at reduced speed, if speed control of the induction motor is obtained by rotor resistance. The commutator motor can be used efficiently at hyper-synchronous speeds, whereas the induction motor is restricted to sub-synchronous speeds.

For equal efficiency, an A.C. commutator machine is usually rather heavier and more expensive than the corresponding D.C. motor. On the other hand, it is a great practical advantage to have a machine which equals or even excels the D.C. motor in point of flexibility of control of torque and speed. This consideration is becoming ever more important as one distribution network after another is changed to A.C. supply. In many instances, A.C. commutator motors can be used where it would otherwise be necessary to install converting apparatus to supply D.C. motors. At the time of writing (1932), the various types of A.C. commutator motors are used more extensively on the Continent than in the United Kingdom, but their undoubted merits will ultimately win equal recognition in all countries.

Speed ranges of from 2 to 4:1 are commonly provided with continuous gradation throughout, and the sizes of A.C. commutator motors usually extend from 1 or 2 H.P. up to about 1 000 H.P., larger machines being occasionally built for traction or similar service. Standard sizes of single-phase and 3-phase commutator motors generally go up to 40 or 50 H.P.; larger sizes up to 250 H.P. are fairly common; and still larger machines up to 3 000 H.P. are built to meet special requirements.

Large numbers of A.C. commutator motors are used for general industrial purposes, including the driving of textile and paper-making machinery, printing machines, cranes, hoists, mechanical stokers, machine tools, pumps, fans, and so on. Heavier applications are in traction service and mine hoists or winding engines.

As compared with induction motors, A.C. commutator motors offer high starting torque, high power factor, and wide range of speed control. On the other hand, the commutator and brush-rocking gear add to the cost and weight of commutator motors and, for some types of the latter, expensive switchgear is required in order to provide variable tapplings. For similar reasons, A.C. commutator motors are more complicated and expensive than the corresponding D.C. machines.

700. Single-Phase Series Motors. Theoretically, any D.C. series-wound motor may be operated on single-phase A.C. supply, for the current necessarily reverses simultaneously in both the field and the armature windings, hence the torque remains constant in direction * but pulsates from zero to a maximum and back to zero again once in each half-cycle of the supply current. Actually, however, when the supply is alternating, the magnetic circuit of the stator must be laminated like that of the rotor and for the same reason (§ 82, Vol. 1). Also, in the interests of high power factor and satisfactory commutation, it is necessary to design the A.C. series motor for operation with a relatively weak field, and to provide a compensating or neutralising winding to counteract the armature reaction. This winding, (cf Fig. 300), may be connected in series with the field winding *F* and armature *M*, or it may be

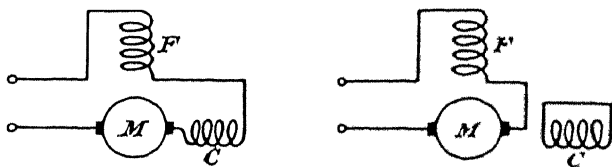


FIG. 300. Single phase series motors.

short-circuited on itself, the requisite current then being induced in it by transformer action from the armature. The compensating winding improves both the P.F. and the commutation of the motor. Another distinctive feature of the A.C. series motor is that the field winding is usually placed in slots on the stator, as in the induction motor, instead of on salient poles as in the D.C. motor. Small series motors, *e.g.* fractional-H.P. machines as used for small fans, are regularly built for operation on either D.C. or single-phase A.C. (§ 710), but the larger sizes of single-phase series motors differ materially from D.C. series motors in construction, though the principle is the same in both cases.

As shown by Fig. 301, the load characteristics of a single-phase A.C. series motor are broadly similar to those of a D.C. series motor (*see* Fig. 261), except that the speed does not vary so rapidly with changes in load. The starting torque is high, much higher than

* Whether the supply be D.C. or A.C., the only method of reversing the torque of a series motor is by interchanging the connections to *either* the field *or* the armature (*not both*).

that of an induction motor, and the speed decreases with increasing load. Speed control is effected more easily than in the D.C. series motor, a transformer with multiple tapplings being used to vary the voltage applied to the motor (§ 732). The motor can be designed to run at higher than the synchronous speed on full-load and, like the D.C. series motor, its principal application is to traction service, for which purpose motors up to several thousand H.P. may be used. A low frequency of supply, say $16\frac{2}{3}$ cycles/sec., is generally

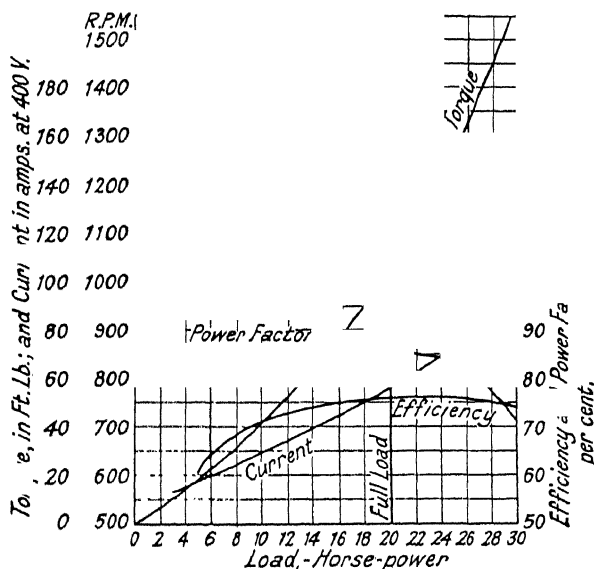


FIG. 301.—Typical characteristics of 1-ph. series or repulsion motor: rated output 20 H.P., 1 000 r.p.m. (see Figs. 247, 250, 251).

employed in such cases, in the interests of high P.F. and good commutation. Smaller single-phase series motors, up to 100 H.P. or so, are used for driving cranes, hoists, boiler-house fans, and similar service, speed control being frequently provided over a range of 2 or 3 : 1. For use on high voltage supply, the field winding can be connected directly to the mains, the armature being fed through a step-down transformer, and the whole of the starting, regulating and reversing gear being in the low-voltage circuit. The inherent tendency of the machine to race on light load may be overcome by a pair of short-circuited brushes set on an axis at right

angles to that of the main brushes: a field is then produced, aiding the main field and increasing in strength as the speed rises until equilibrium is attained. Interpole windings are used in all but the smallest machines to improve the commutation.

The single-phase series motor is more expensive than an induction motor, sometimes two or three times as costly, but it is applicable to services for which the "shunt" characteristics of the induction motor are unsuitable. The efficiency of the series motor is rather lower than that of the induction motor, say 65 to 70% in a 1-2 H.P. machine, 75 to 80% in a 20 H.P. machine, and 80 to 85% in 50-100 H.P. machines. The P.F. is usually about 0.85 at rated full-load, falling to 0.8 on overload and rising to 0.9 on light loads. These figures are representative but can be varied by modifying the design of the motor.

The control of single-phase series motors is discussed in § 732.

701. Single-Phase Repulsion Motors. The plain single-phase repulsion motor is a series-type motor with the armature brushes short-circuited, current being induced in the armature winding by the transformer action of a winding on the stator. There is no electrical connection between the supply and the armature, hence the machine can be used on high-voltage supply without the cost and complication of a special transformer to feed the armature.

If, instead of short-circuiting the compensating winding *C* and conducting current into the armature, as shown in the right-hand diagram, Fig. 300, we conduct current through the winding *C* and induce it in the armature, the brushes being short-circuited, we obtain the arrangement shown in Fig. 302.* (Going further, we may replace the two separate windings on the stator by a single winding designed to produce the same resultant field (Fig. 303), thus arriving at the simplest possible form of the repulsion motor.

Thus, in Fig. 302, the field or excitation winding *F* establishes the motor field, and the 'transformer winding' *C* induces the armature current, while interaction between the field and the armature current produces the motor torque. The single stator winding *S*, Fig. 303, produces a field on the *XX* axis, and this field may be regarded as the resultant of components along the lines

* The reversing switch *R* is included for the purpose of later explanation and has nothing to do with the principle of the motor itself.

F and C , these components being equivalent respectively to the separate stator windings in Fig. 302.

If the short-circuited brushes were placed on the line YY , in Fig. 303, at right angles to the line XX , the coil S would act simply as a field winding. There would then be no component of the field along the short-circuit axis of the armature, *i.e.* no component corresponding to the winding C , Fig. 302, hence no current would flow in the armature and the motor would develop no torque. The line YY , Fig. 303, perpendicular to the axis XX , is the 'neutral axis,' and when the brushes are displaced from this axis the armature rotates in the *opposite* direction, whence the name 'repulsion' motor. Usually the angle α is between 10 and 20

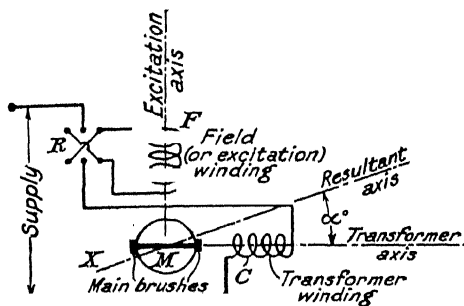


FIG. 302.—Single-phase repulsion motor (Atkinson type).

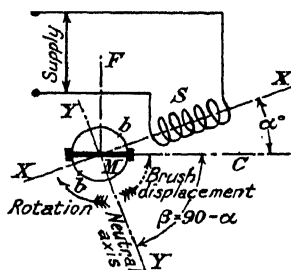


FIG. 303.—Single-phase repulsion motor (Elihu Thomson type).

degrees, *i.e.* the brush axis is displaced between 70 and 80 degrees from the neutral axis, YY , under the normal running conditions. In order to reverse the direction of rotation, the brushes must be displaced in the opposite direction from the neutral axis, *i.e.* to the position bb , Fig. 303; *see also* Fig. 304. This is equivalent to setting the winding S on an axis a° below the brush axis C , instead of a° above it as shown in Fig. 303; or, referring to Fig. 302, it is equivalent to reversing the connections of F with regard to the transformer winding C . Reversing the connections of the single winding S would obviously have no effect (the current in this winding is reversed every half-cycle of the supply); in order to reverse the rotation of the motor, the relative displacement between the axis XX and the brush axis must be reversed.

If the short-circuited brushes were placed on the axis XX , the winding S , Fig. 303, would act simply as the transformer winding C , Fig. 302. A heavy current would be induced in the armature, but there would be no field component, hence the motor would develop no torque (see Fig. 304). This is called the 'short-circuit' position of the brush axis. If the brushes were moved still further in an anti-clockwise direction, *i.e.* beyond the line XX and towards bb , Fig. 303, the motor would start in the opposite direction, but this is not the correct method of reversal because a very heavy current flows through the armature when the brush axis coincides

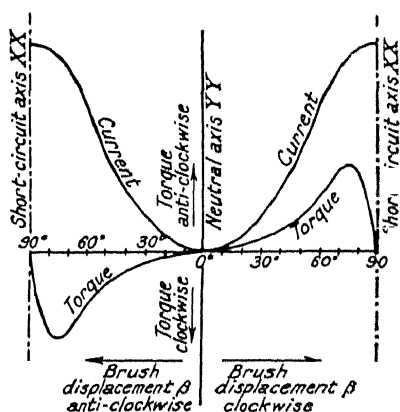


FIG. 304.—Variation of current and torque of repulsion motor with displacement of brushes from neutral axis (see also Fig. 303).

with XX . The correct procedure is to move the brushes back from the line C to the neutral axis YY , in which position the armature current as well as the torque is zero, and then to move the brush axis clockwise towards the position bb , whereupon the motor starts to run in an anti-clockwise direction.

(Changing the angle α , Fig. 303, or the complementary angle β ($90^\circ - \alpha$) = angle of displacement of the brush axis from the neutral axis, is equivalent to varying the ratio between the ampere turns

of the field and transformer windings, Fig. 302, and its effect is to vary the characteristics of the motor as follows: Increasing the angle β of brush displacement reduces the field component and therefore increases the speed and reduces the torque for a given current. Conversely, reducing β reduces the transformer component, the speed therefore decreases and the torque for a given current increases (see also Fig. 369, § 733).

Brush displacement from the neutral axis is a convenient means of starting and reversing the plain repulsion motor of the single stator winding type, but it is not a very satisfactory means of speed control, partly because it is very sensitive, a small change in brush position resulting in a relatively large change in speed, and partly

because the P.F. is low and the commutation bad when the brushes are far from their normal operating position. Nevertheless, motors of this type are used industrially where speeds from zero up to 1.2 or 1.3 times synchronous speed are required, *i.e.* up to about 3 750 r.p.m. for a 2-pole and 1 875 r.p.m. for a 4-pole, 50-cycle machine, most of the running being in the neighbourhood of synchronous speed.

The starting torque of a repulsion motor is high, about $2\frac{1}{2}$ times full-load torque with twice full-load current. Commutation is excellent at or near the synchronous speed but poor at speeds much above or below the latter. The P.F. is low at starting (about 0.4) but increases with speed. The operating characteristics resemble those of a single-phase series motor (Fig. 301, § 700), *i.e.* the machine is liable to race on light load and its speed decreases as the load-torque increases. The speed of the machine varies approximately inversely with the field, and the latter varies with the load, within the limits of magnetic saturation. The speed of the motor is approximately proportional to the applied voltage.

The efficiency of a repulsion motor developing 15 to 30 H.P. at speeds from 700 to 1 000 r.p.m. is usually about 80 to 85 %, the P.F. ranging from 0.8 to 0.9.

Single-phase repulsion motors up to 30 or 40 H.P. are used mainly to drive fans, centrifugal pumps, spinning machines, printing machines and hoists; larger sizes can be built if required.

702. Déri Repulsion Motor.—The distinctive feature of this machine is the use of two sets of brushes, as shown diagrammatically in Fig. 305. One set of brushes is fixed on the excitation axis, but the other set is movable.

When the stationary brushes F and the movable brushes M are both on the excitation axis (*see* Fig. 305 (a) in which the brushes are shown on each side of the axis XX for clearness, instead of both on this axis), they

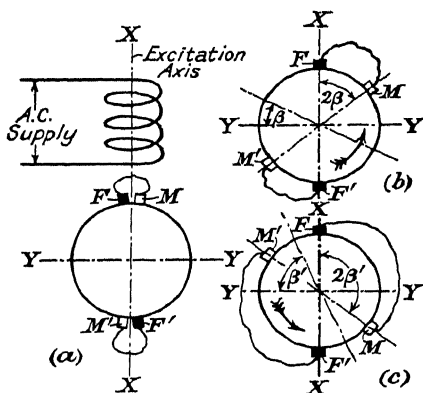


FIG. 305.—Illustrating principle of Déri 1-ph. repulsion motor.

are equivalent to a single pair of short-circuited brushes on the 'neutral axis' YY . If the movable brushes be displaced through an angle 2β from the axis XX , Fig. 305 (b), this is equivalent to shifting a single pair of short-circuited brushes through an angle β from the neutral axis YY . Similarly, if the brushes MM be displaced $2\beta'$ from the axis XX , Fig. 305 (c), this is equivalent to a displacement β' of a single pair of short-circuited brushes. In other words, the actual brush movement $2\beta' \div 2\beta = 2(\beta' - \beta) =$ twice the effective angle of brush shift. The Déri motor is therefore less sensitive than the ordinary repulsion motor to changes in brush position. The angle through which its brushes must be rocked is twice that through which the brushes of a simple repulsion motor have to be moved for the same effect.

If M were brought alongside E' , and M' alongside E in Fig. 305 (c), the arrangement is clearly that of an ordinary repulsion motor with the brushes on the excitation axis, *i.e.* in the 'short-circuit' position (§ 701), but the displacement of the brushes from the neutral position is 180 degrees instead of 90 degrees as in the ordinary repulsion motor.

The double brush sets of the Déri motor divide the armature winding into two zones, one of which is compensating, with the result that commutation and power factor are improved.

703. Series-Repulsion (Compensated) Motors. The principle of the single-phase series-repulsion motor is illustrated by

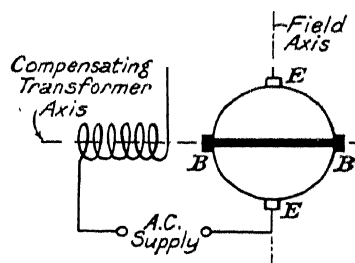


FIG. 306.—Single-phase series-repulsion motor.

Fig. 306. The short-circuited brushes BB are on the 'transformer axis' (§ 701), and the field is produced by the armature winding itself, current for this purpose being led in by brushes EE at right angles to BB (in a two-pole machine) connected in series with the stator winding as shown. The exact nature of the electro-

mechanical action in this machine is debatable; * for practical purposes it is sufficient to regard it as being due to interaction between the exciting flux or

* For a detailed consideration of the theory of the machine and its vector diagram on load, see 'A.C. Commutator Motors,' by W. Ford, *El. Rev.*, Oct. 12, 1928, p. 595.

'field' of the machine and the rotor short-circuit current. A certain amount of phase-compensation occurs in this type of motor, whence the name 'compensated repulsion motor.'

A serious objection to the simple series-repulsion motor is that the machine cannot be connected directly to high-voltage supply because there is electrical connection between stator and rotor; this objection may be overcome by using a double-wound transformer between the stator and the excitation brushes *EE*, as in the Latour-Winter-Eichberg motor (Fig. 307). The P.F. of this machine is materially higher than that of the ordinary repulsion motor and is unity or near unity at speeds above or equal to synchronism. The machine can be reversed by a reversing switch *R* in the connections

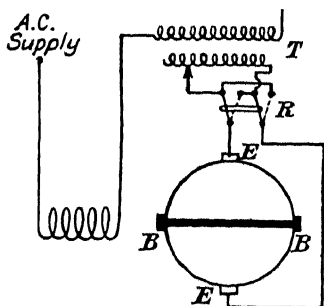


FIG. 307.—Latour-Winter-Eichberg compensated repulsion motor.

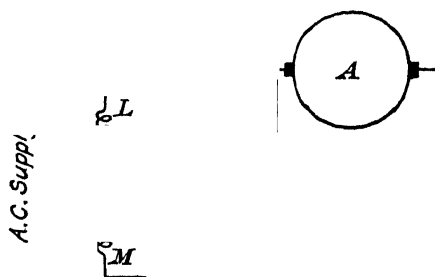


FIG. 308.—Series-repulsion motor with variable-ratio stator and armature supply.

to the excitation brushes *EE*. Motors of this type have been used extensively for traction purposes. For each tapping of the transformer *T* the motor has a series characteristic, and starting and speed control can be effected conveniently by varying the tapping in use. The kVA-capacity of the transformer *T* is small, *viz.* that required to magnetise the machine.

In Fig. 308 the whole input to the motor is taken through a double-wound transformer, the secondary of which has a tapping so that the ratio of energy supplied to the stator windings *T* and *F* on the one hand and the armature *A* on the other can be varied. When the tapping *J* is at *M*, the armature is short-circuited and the motor runs as a plain repulsion machine but, with *J* in an intermediate position, part of the supply to the armature is by

conduction as in a series motor. By moving the tapping J , speed control is obtained and good commutation is maintained over a wide range of speed. This arrangement has been used in heavy traction service, but the simpler compensated-series type is now generally employed.

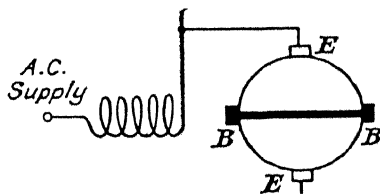


FIG. 309.—Single-phase series compensated motor; excitation supply taken from auto-transformer (see also Fig. 310).

An intermediate type of single-phase series compensated repulsion motor is shown in Fig. 309. The excitation brushes of the armature are connected to an auto-transformer which reduces the voltage without, however, entirely isolating the latter from the main supply. The curves in

Fig. 310 * show the high and low limits of torque at various speeds for a motor of this type. An intermediate curve is shown dotted;

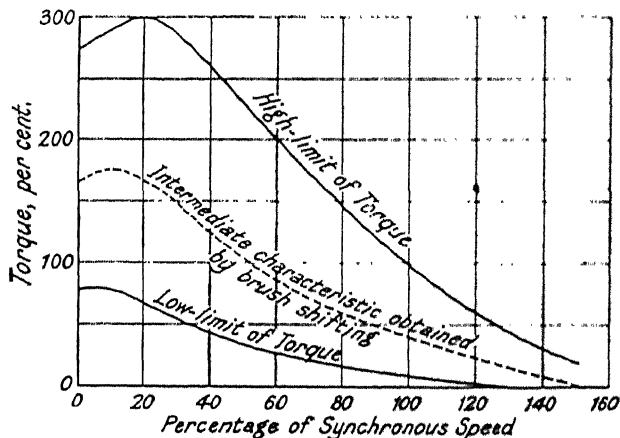


FIG. 310.—Torque-speed curves for 1-ph. series compensated motor (as in Fig. 309).

other similar curves, intermediate between the high and low limits, can be obtained by brush-shifting. It will be seen that brush-

* Based on data relating to a General Electric (Schenectady) BSS machine, see *Gen. El. Rev.*, Vol. 24, p. 930.

shifting produces comparatively little change in speed at light load, *i.e.* when the torque is very low, but a wide range of speed is available at higher loads, and generally about 2:1 at full-load torque. For any given brush-setting the speed varies with the torque according to a limited, *i.e.* non-racing, series characteristic as shown. The starting current and starting torque vary approximately as in Table 126.

TABLE 126.—*Starting Characteristics of Single-Phase Series-Repulsion Motor* (as in Fig. 309).

Percentage of Synchronous Speed at Full-Load Torque.*	Starting Torque, per cent. of Full-Load Value.	Starting Current, per cent. of Full-Load Value.
0	100	110
20	110	125
40	140	140
60	180	170
80	240	230
100	275	300

* Determined by brush position.

The starting current can be limited by starting with the brushes in the low-speed position (Table 126), and the rate of acceleration is determined by the rate at which the brushes are shifted. A 5 H.P. motor of this type runs at about 80 % efficiency and 1.0 P.F. at full-load torque and synchronous speed, and at about 65 % efficiency and 0.75 P.F. at full-load torque and half-speed.

704. Repulsion-Induction Motors.—Machines of this type start as repulsion motors and run as induction motors, thus combining the high starting torque and series characteristic of the repulsion motor with the practically constant running speed (shunt characteristic) of the induction motor. Generally, the starting and running characteristics of the repulsion-induction motor are superior to those of a split-phase induction motor.

The repulsion-induction motor has one single-phase winding on the stator, and an armature resembling that of a D.C. motor. It starts as an ordinary repulsion motor (§ 701) and when it has reached 70 or 80 % of synchronous speed the armature is short-circuited. This may be effected automatically by a centrifugal device which short-circuits the commutator and lifts the brushes,

thus virtually converting the armature to a squirrel-cage rotor. Alternatively, three points on the armature winding 120 electrical degrees apart may be connected permanently to slip rings, the latter being on open external circuit during the starting period; sets of brushes 180 electrical degrees apart on the commutator are short-circuited during the starting period. When it is desired to change from repulsion to induction operation, the slip rings are connected externally through resistances arranged in star, these resistances being then reduced and finally short-circuited. The current surge

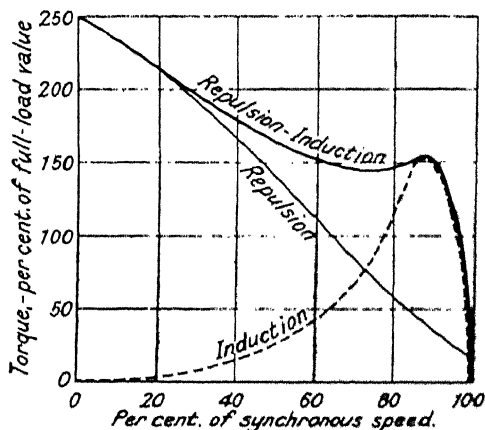


FIG. 311.—Torque-speed curves for induction, repulsion and repulsion induction motors.

and mechanical shock resulting from abrupt short-circuiting of the armature are thus avoided.

Typical torque-speed curves for ordinary induction, ordinary repulsion and combined repulsion-induction motors are given in Fig. 311. The starting torque of the repulsion-induction motor is from 2 to 3 times full-load torque with from $1\frac{1}{2}$ to $2\frac{1}{2}$ times full-load current when starting on full voltage, according to the resistance between the commutator brushes and the details of the design of the machine. If series resistance or other means of reducing the voltage be used during the starting period, the motor may start with from 1 to $1\frac{1}{2}$ times full-load torque and full-load current.

The use of slip rings and a variable external resistance is one method of avoiding an abrupt increase of torque when changing

from repulsion to induction working. Another method is to use a special type of double-wound rotor containing a commutated winding as the repulsion element and a deeply embedded squirrel-cage winding which contributes a smoothly increasing proportion of the total torque of the motor as the machine accelerates. It is claimed that motors built on this principle combine practically perfect commutation with a P.F. of about 0.95 over the running range.

Since the repulsion-induction motor runs normally as an induction motor, its operating characteristics are those of an induction motor and it is incapable of speed control. The high starting torque makes this motor useful in lifts and in other applications where it is desirable to combine powerful acceleration with nearly constant speed at all loads during normal running.

705. Synchronous-Repulsion Motors.—This type of motor has been developed to provide, as desired, a constant-speed (synchronous) drive or an adjustable speed up to, say, $1\frac{1}{2}$ times the synchronous speed of the machine. It was developed primarily for driving cinematograph projectors which may need to be driven at a definite speed for the projection of talking motion pictures or at an adjustable speed for silent pictures; * no doubt it will find other applications in similar circumstances, particularly for fractional-H.P. outputs.

The machine consists essentially of a synchronous motor and a repulsion motor combined in a single magnetic circuit and using the same windings, as shown diagrammatically in Fig. 312, where *S* represents the stator winding; *C*, the rotor winding, serving as repulsion armature and D.C. exciting winding; *B*, the brushes on

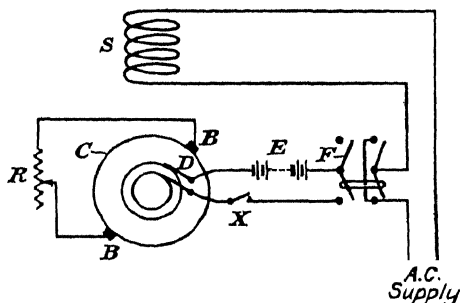


FIG. 312.—Synchronous-repulsion motor.

* See 'The Synchronous-Repulsion Motor,' by H. C. Specht, *Jour. Amer. I.E.E.*, May 1930, p. 346, whence the present notes are derived, for a detailed statement and explanation of the characteristics of this machine.

the commutator; and *D*, the brushes on the slip rings. A regulating resistance *R* is connected between the brushes *B*; a storage battery *E*, or other source of D.C., is connected in the slip-ring circuit; a centrifugal or other automatic switch *X* is provided; and the change-over switch *F* is connected as shown. When *F* is closed on the upper pair of contacts, the motor operates as an ordinary repulsion motor (§ 701), speed control being effected by the resistance *R*. On the other hand, with *F* closed on the lower pair of contacts, the D.C. excitation establishes magnetic poles in the armature

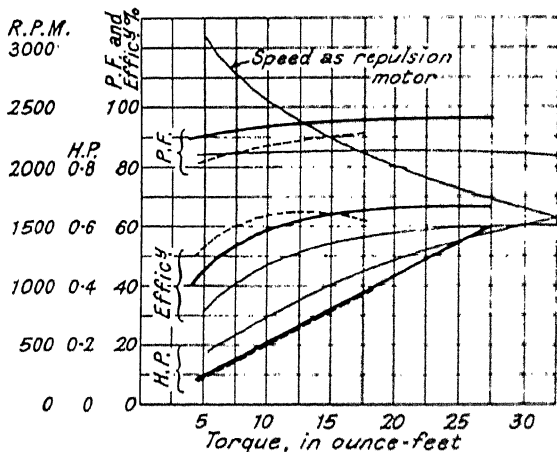


FIG. 318.—(Characteristics of $\frac{1}{4}$ H.P., 60-cycle, 220 V, 4-pole, 1 ph. synchronous-repulsion motor.

Thin dotted curves.—Machine operated as a synchronous motor with 12 A, D.C. excitation, repulsion brushes lifted speed constant at 1 200 r.p.m.

Thin solid curves.—Machine operated as ordinary repulsion motor. Speed variable.

Thick solid curves.—Machine operated as synchronous repulsion motor with 12 A, D.C. excitation. Speed 1 800 r.p.m.

which lock with the rotating field set up by the repulsion motor; the machine therefore comes up to speed, pulls into step and runs as a synchronous machine. A flywheel prevents hunting during synchronous operation.

The motor can be operated synchronously with its slip rings short-circuited, but its pull-out torque is greater, its operation more stable, and its P.F. higher if the D.C. excitation be maintained.

Fig. 313 shows test curves relating to a motor of this type operated successively as a synchronous, a repulsion, and a syn-

chronous-repulsion machine. The efficiency curves in this figure do not allow for the D.C. excitation input. The pull-out torque as a synchronous motor was 20 oz.-ft.; the repulsion motor torque at 1 800 r.p.m. was 26 oz.-ft.; and the measured pull-out torque as a synchronous-repulsion motor was 50 oz.-ft. As a synchronous-repulsion motor, the starting torque was 90 oz.-ft. and the pull-in torque was 24 oz.-ft.

706. Single - Phase Commutator Motors with Shunt Characteristics.—Motors of this type are often called ‘single-phase shunt’ motors for brevity. Like D.C. shunt-wound motors, they run at nearly constant speed at all loads within their range, and their excitation is independent of the load. There, however, the analogy ends. Subject to certain practical reservations (§ 700), a D.C. series-wound motor can be used on A.C. supply, but this is not true of a D.C. shunt-wound motor. If the latter were connected to an A.C. supply, the field produced would lag 90° behind the applied P.D.; there would be practically 90° difference in phase between the main field and the armature current, hence no appreciable driving torque would be produced.

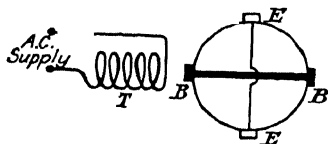


FIG. 314.—Single-phase commutator motor with shunt characteristics.

The principle of the single-phase shunt-type commutator motor is illustrated by Fig. 314 (2-pole machine). Two sets of short-circuited brushes are employed, one on the axis of the stator winding *T*, and one at right angles thereto. The current flowing between *BB* is due to the transformer action of *T*, and *when the machine is running* there is current flowing between *EE* due to the E.M.F. produced by rotation of the armature. The flux on the *BB* axis, and therefore the E.M.F. of rotation, is in quadrature with the voltage applied to the stator winding. The current on the *EE* axis and the flux which it produces lag practically 90° on the E.M.F. of rotation. Hence the flux on the *EE* axis is in phase with the voltage applied to *T* and, so is the current between *BB*; in other words, the flux on the excitation axis is in phase with the current on the transformer axis and a driving torque is produced.

In this simple form, however, the motor has no starting torque and it can only run near synchronous speed. Also, in regard to

torque, P.F. and efficiency it is inferior to the single-phase induction motor (§ 689), besides involving the use of a commutator.

The characteristics of the motor can be improved by connecting a compensating winding on the axis of *T* between the brushes *EE*, thus injecting a voltage in phase with the applied voltage into the exciting circuit and raising the P.F. Similarly, speed control can be obtained by injecting a variable P.D. between the brushes *BB* (see also § 734). The motor can be started as a repulsion motor by opening the connection between *EE*; the starting torque is then high.

Modern single-phase, shunt-type commutator motors with phase compensation and provision for speed variation maintain a power factor near unity down to about one-third of full-load. The efficiency is usually 4 or 5 % lower than that of D.C. motors up to 5 H.P. and 2 or 3 % lower than that of D.C. machines in 50 H.P. units. Generally, the A.C. machine is 10 to 15 % dearer than the equivalent D.C. motor, but it may be 20 to 30 % lighter.

The control of these motors is discussed in § 734, where, also, particulars are given of a two-speed machine for lift service.

707. Three-Phase Commutator Motors.—Two single-phase repulsion motors coupled mechanically can be supplied electrically by the two secondary phases of a Scott Tee-transformer (§ 394, Vol. 2), and this arrangement is sometimes employed; the speed of the coupled motors can be varied like that of a single machine, and the load on the 3-phase supply is balanced. Generally, however, it is preferable to use a 3-phase commutator motor. This is a single machine and shunt or series characteristics can be obtained as desired. By the use of auxiliary transformers and/or self-inductances a 3-phase series or shunt type motor can be compounded, *i.e.* its characteristics can be made to resemble those of a D.C. cumulatively compounded motor (§ 677). The no-load speed of such a machine is limited, and the decrease in speed between no-load and full-load is more or less considerable according to the degree of compounding.

The cost of a 3-phase commutator motor is generally higher than that of a slip-ring induction motor with speed-regulating resistance, but this is more than counterbalanced by the higher efficiency of the commutator motor if operation is required for any considerable time at reduced speed. If it is desired to run at reduced speed only occasionally and for short periods, the slip-ring

induction motor may be more economical than a 3-phase series motor; but if, in addition to speed control, it is desired that the speed selected be maintained practically independent of load, then a 3-phase shunt motor should be employed.

Current being supplied to the stator and rotor of a 3-phase commutator motor either by direct conduction or through a static transformer, the supply frequency is maintained in both windings at all speeds. The 'slip energy' of the machine is taken from or fed to the supply mains according as the rotor speed is below or above synchronism.

Apart from their use as independent machines, 3-phase commutator motors offer a convenient means of utilising the slip energy of large induction motors, thus allowing the speed of the latter to be varied continuously and efficiently (§ 694).

708. Three-Phase Series-Type Commutator Motors.—In general, the stator winding of a 3-phase series-type commutator motor resembles that of a 3-phase induction motor, except that both ends of each phase-winding are brought out; while the rotor is similar to the armature of a D.C. machine. The stator and rotor are connected in series *via* the commutator brushes, either directly or through a transformer. The characteristics of the machine resemble those of a D.C. series-wound motor in that the speed decreases with increasing load, but, whereas the D.C. series motor races on light load, the 3-phase series motor with intermediate transformer has a definite no-load speed, usually about $1\frac{1}{2}$ to $1\frac{3}{4}$ times the synchronous speed, imposed by the saturation of the rotor transformer. The motor can be started, reversed and controlled in speed by shifting its brushes; alternatively, the motor can be started by a variable-tapping transformer, and reversed by interchanging two supply leads. Electrodynamic braking is effected if the brushes are moved back through the neutral position, but the frequency of the current generated decreases as the motor slows down, hence the energy can only be dissipated as heat, and not returned to the supply mains. The range of speed control at full-load torque is usually about 3:1, but ranges up to 6:1 can be obtained without instability if desired. It is easier to design this type of motor for 25-cycle than for 50-cycle supply and, though larger machines can be built, up to 1 000 H.P. or so for rolling mills or winding engines, the usual limit for standard commercial motors is about 150 H.P. for 25-cycle and 100 H.P. for 50-cycle supply.

The purpose of the intermediate transformer, between stator and rotor, is to reduce the voltage applied to the commutator, usually to 50 to 100 V; and this transformer deals only with the power fed to the rotor. If necessary, another transformer is used between the mains and the stator where a.h.t. supply is concerned. Three typical arrangements are shown in Figs. 315 to 317.

In Fig. 315 the transformer is connected between the mains and the stator, and must therefore be rated for the full motor output. Also, the stator will be heavy as it is connected electrically to the brushes and must therefore be designed for low

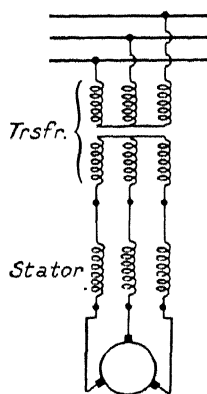


FIG. 315.—Three-phase series motor with transformer between mains and stator.

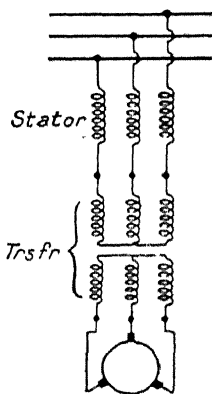


FIG. 316. Three phase series motor with transformer between stator and rotor.

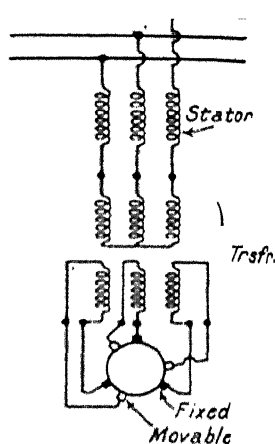


FIG. 317. Three-phase series motor with transformer between stator and rotor and a double set of brushes.

voltage. A further objection is that the motor is liable to race on light load and must therefore be provided with a centrifugal switch. This arrangement is seldom employed.

In Fig. 316, which represents the arrangement generally employed, the transformer is between the stator and rotor and has only to deal with the 'slip energy,' i.e. the energy in the rotor circuit. The increasing saturation of the transformer limits the speed of the motor on no-load. For $n\%$ variation of speed from synchronism, the kVA capacity of the transformer is about $n\%$ of the motor kVA at synchronism. It is therefore more economical to secure the desired speed variation by working above and below synchronism rather than on either side of synchronism alone, apart from the fact that the commutation is better and the efficiency and power factor higher when working at or near synchronism.

Fig. 317 shows the same arrangement as Fig. 316 except that each phase of the secondary winding of the transformer is now connected between a fixed and a movable brush (or line of brushes). The advantage of this arrangement is that

displacement of the movable brushes reduces the ratio of stator to rotor turns as the speed is increased and thus secures stable running over a wide range of speed without sacrifice of power factor. It is claimed, however, that the latest 3-phase series motors fulfil practical requirements in this respect when arranged as in Fig. 816, *i.e.* without the complication of a second set of brushes.

The torque-speed characteristics of a 3-phase series motor may be regarded as intermediate between those of an induction motor and a D.C. series motor. Thus, Fig. 318 shows diagrammatically the case of a 3-phase series motor which, with 175° brush displacement, develops a rapidly increasing torque as the speed is reduced until the point *A* is reached; at yet lower speeds, the

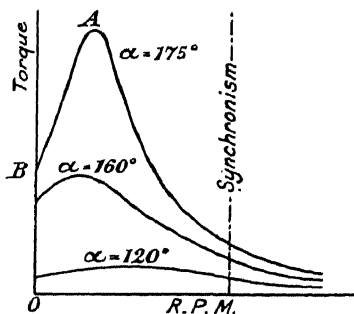


FIG. 318.—Diagrammatic representation of instability at low speeds in a 3-ph. series motor.

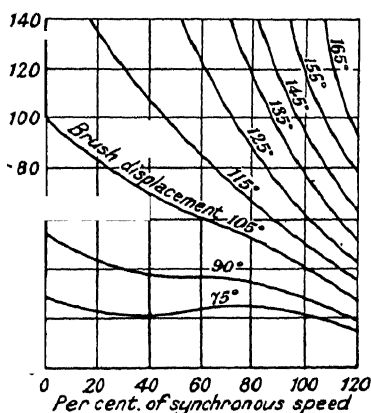


FIG. 319.—Torque-speed curves of 3-ph. series motor for various brush settings.

torque decreases and the operation of the motor becomes unstable on the part *AB* of the curve. The characteristic curve is similar but less pronounced at smaller displacements of the brushes, and the torque decreases rapidly as the brush-displacement is reduced. A modern 3-phase series motor has no such points of instability within its operating range, a typical set of torque-speed curves being as shown in Fig. 319; there are, of course, innumerable intermediate curves, one for each brush position. These curves are roughly similar to those of an induction motor with variable rotor resistance. High starting torque can be obtained and the torque-speed characteristic is of the series type; the starting torque per ampere is, however, higher than in the induction motor and the speed gradation is now continuous.

According to the design of the machine and its range of operation, the P.F. of the 3-phase series motor is high (slightly lagging or leading) and is well maintained over a considerable range of load. The machine cannot, however, be used for general P.F. improvement in the same way as the synchronous motor. Typical values of efficiency and power factor at constant torque are: efficiency, 85 % at synchronous speed and 75 % at half synchronous speed; P.F., 0.95 and 0.6 respectively. The P.F. may be leading at super-synchronous speeds on light load.

The usual applications of 3-phase series-type commutator motors are substantially the same as those of D.C. series-wound motors, *viz.* haulage winches, hoists, shears, centrifugal pumps, fans, blowers, and sometimes rolling mills, winding engines, locomotives, etc. The starting torque is higher than that of an induction motor, and the 3-phase series motor can be used with advantage in convenience and efficiency in most cases where a slip-ring induction motor with variable rotor resistance might be employed. The 3-phase series motor is specially suitable for constant torque loads, or for variable torque loads in which a decrease of speed with increasing torque is desired; the use of an automatic brush-setting regulator enables constant speed to be maintained at variable torque if desired. The 3-phase series motor is usually cheaper and more efficient than the corresponding 3-phase shunt motor, but its variable speed may be an objection.

709. Three-Phase Shunt-Type Commutator Motors.—

A 3-phase commutator motor of the shunt-type is so called because its load-speed characteristics resemble those of the D.C. shunt-wound motor and, as in the latter, the field does not vary with the load. Broadly speaking, the stator of a 3-phase shunt motor resembles that of a 3-phase induction motor, while the rotor has a winding and commutator resembling those of a D.C. machine. In some instances, a variable-ratio transformer is used in conjunction with the motor; and, in other cases, auxiliary windings are employed on either the stator or the rotor. The basic principle consists in applying an E.M.F. of line frequency to the brushes, this E.M.F. aiding or opposing the E.M.F. induced in the rotor winding by the rotation of the latter. The commutator acts as a frequency-changer between the line frequency in the brush leads and the slip frequency in the rotor windings. Speed control

is obtained by varying the E.M.F. applied to the brushes; when this aids the induced E.M.F., the motor runs at higher than synchronous speed, but when it opposes the induced E.M.F., the motor runs below synchronism. The motor can thus be set to any desired speed within its range, this speed being nearly independent of load except at low speeds when the decrease in speed with increasing load is considerable, as shown diagrammatically in Fig. 320. By altering the phase of the E.M.F. applied to the brushes, the P.F. of the machine can be adjusted and, if desired, the motor can be made to operate at leading P.F. at full-load.

From the descriptions given below it will be seen that the 3-phase shunt motor is essentially a compensated induction motor, the commutator in which enables the slip to be regulated to any

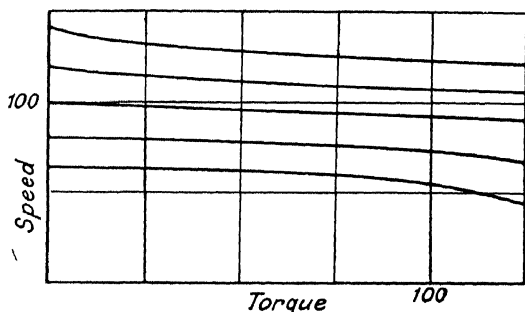


FIG. 320.—Speed-torque curves of 3-ph. shunt motor (diagrammatic).

desired positive or negative value (below or above synchronism), without the loss occasioned by rheostatic control, and without the variations of speed with load occasioned by rheostatic control. A speed range of 3 : 1 is usually sufficient, *e.g.* from 1 500 to 500 r.p.m. if the synchronous speed of the motor is 1 000 r.p.m. A further reduction of speed, down to crawling speeds, may be obtained, as in slip-ring induction motors, by inserting resistance in the secondary circuit, but this method should be used only for temporary purposes since it involves rheostatic losses. Usually, from $1\frac{1}{2}$ to 2 times full-load torque is obtained on starting at full voltage, with about $1\frac{1}{2}$ times full-load current, but a starting torque of from $2\frac{1}{2}$ to 3 times the normal full-load torque can be obtained if desired in the latest machines of this type.

Shunt-type A.C. commutator motors may be stator-fed, rotor-fed, or double-fed, *i.e.* the connections from the supply mains go

to the stator windings, the rotor windings, or both, as the case may be. The principle of operation is the same in each case.

Fig. 321 shows diagrammatically the connections of a double-fed motor. The stator may be connected directly to the supply mains, even in the case of H.T. supply; and the connection between the mains and the rotor is through a variable-ratio, step-down transformer, so that the E.M.F. applied to the commutator does not exceed, say, 300 to 350 V. The transformer *T* feeds slip-energy to or from the rotor, and its effective voltage ratio at any moment determines the speed of the machine. Reversal is effected by interchanging two stator leads and also two rotor leads.

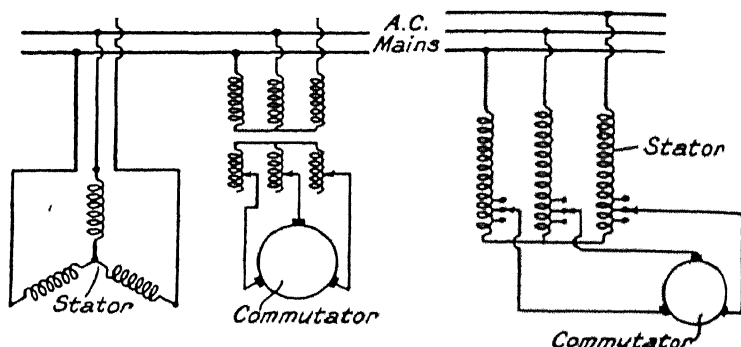


FIG. 321.—Double-fed shunt type 3-ph. commutator motor. FIG. 322.—Stator-fed 3 ph. shunt motor with rotor connected to statorappings.

The use of a separate step-down transformer in the rotor circuit may be avoided by using the stator windings as an auto-transformer, the brush leads being then taken to tappings on the stator winding, as shown diagrammatically in Fig. 322. To obtain speeds above synchronism, the stator windings must be extended and provided with tappings beyond the star point. This arrangement, like that in Fig. 321, provides only for step-by-step control of speed, the number of speeds and the fineness of the gradation being determined by the number of tappings. In either case, P.F. improvement can be effected by connecting a coil from another phase in the brush leads, so as to inject a component of E.M.F. suitably out of phase with the true star voltage. An induction regulator might be used to vary the magnitude and phase of the E.M.F. applied to the rotor,

but an objectionably heavy leading current is then obtained at and near synchronism.

The use of tappings and step-by-step switchgear is avoided, and continuous gradation of speed is obtained, by feeding a 3-phase primary winding on the rotor through slip rings, and connecting the stator (secondary) windings between double brushes as shown in Fig. 323; these brushes are on a commutator the bars of which are connected to an auxiliary regulating winding on the rotor. By moving the *a* and *b* sets of brushes simultaneously in opposite directions, the E.M.F. applied to the stator windings, and hence the speed of the motor, can be regulated continuously. The commutator is relatively small as it deals only with the kVA of 'slip'; below synchronism the regulating winding takes power from the secondary, and above synchronism it supplies power to the secondary. The current in the regulating winding is derived from the primary by transformer action.

When the brushes *a* and *b* are in line the secondary phases are short-circuited and the machine runs as an ordinary

induction motor at synchronous speed less slip. Speed control above or below synchronism, say from $\frac{1}{2}$ to $1\frac{1}{2}$ times synchronous speed, is obtained by displacing the brush sets with regard to each other, still keeping the brushes in each set 120 electrical degrees apart. Inching speeds can easily be obtained by putting resistances in series with the secondary phases. The two windings on the rotor being electrically distinct, star-delta control can be applied to the primary if desired, and there is no electrical connection between the commutator and the H.T. supply. As a matter of interest,

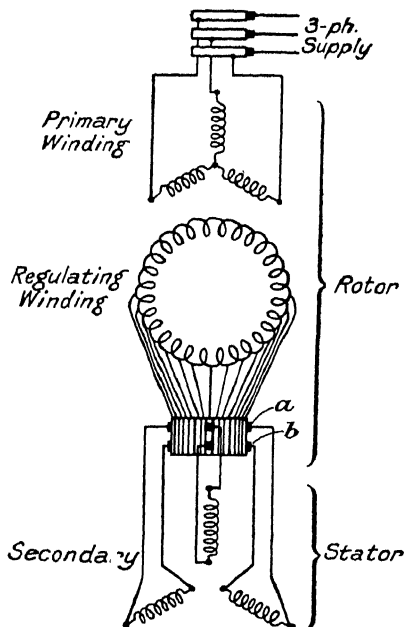


FIG. 323.—Schrage 3-ph. shunt-type commutator motor.

Fig. 323 should be compared with Fig. 360, § 728: if the *b* brushes in Fig. 323 be omitted and the stator winding be connected in star, the machine becomes a compensated induction motor with P.F. control by displacing the brushes *a*, but no provision for speed variation (see Fig. 283, § 688).

This motor, which is probably the most generally useful variable-speed A.C. motor yet developed, is applied to a great variety of purposes where a wide range of speed adjustment is required, and the speed is desired to be practically constant at all loads. Typical ratings range from 5.0 / 1.6 H.P. at 1 500 / 500 r.p.m. up to 100 / 32 H.P. at 720 / 240 r.p.m. (the torque being constant, the H.P. varies with the speed), but ratings outside these limits can be obtained up to about 300 H.P. if required. Typical values of efficiency range from 80 to 85 % at from $\frac{1}{2}$ -load to full-load at synchronous or higher speed; and from 65 to 75 % between half and full-load at the lowest speed (say, half synchronous speed). Typical values of power factor are as follows:—

Load.	$\frac{1}{4}$	$\frac{1}{2}$	$\frac{3}{4}$	1
P.F. at speed (approx.)				
$\frac{1}{2}$ synchronous	0.73	0.76	0.82	0.90
synchronous	0.82	0.77	0.68	0.50
$1\frac{1}{2}$ \times synchronous	1.00	1.00	0.97	0.82

Within limits, the P.F. of the machine can be varied, and kept leading or unity over a considerable range of loads and speeds, by altering the position of the commutator brush gear as a whole with regard to the phase windings on the stator. This may be done by displacing the sets of brushes unequally from the neutral position; in any case, some complication of the brush gear is involved.

Shunt-type machines are the most extensively used type of A.C. commutator motors, because in the majority of industrial driving services it is desired that a fixed or regulable speed should be maintained substantially constant, regardless of variations in load. The shunt-type A.C. commutator motor fulfils these requirements. Hitherto this type of motor has been mainly employed in textile, paper and printing works, but there is no reason why it should not be used much more generally, *e.g.* for driving fans, pumps, machine tools, lifts, stokers, and so on. The high starting torque of modern motors of this type renders them suitable for driving belt conveyors and other machines offering great resistance to starting.

710. Fractional-H.P. Motors: 'Universal' Motors.—The B.S.I. definition of a fractional horse-power motor is one of any continuous rating less than 1 H.P. per 1 000 r.p.m. (*see also* § 670 and B.S.S. No. 170 (1926)). The standard limits of rated voltage for these machines are:—

<i>For D.C. Motors:</i>	
$\frac{1}{2}$ H.P. and above but less than 1 H.P. per 1 000 r.p.m.	100-480 V
Less than $\frac{1}{2}$ H.P. per 1 000 r.p.m.	100-250 V
<i>For A.C. Motors:</i>	
Single-phase	100-250 V
Three-phase	100-250 V

The types of motors most employed in fractional-H.P. sizes are D.C. series, shunt and compound wound machines (§§ 675-677), single-phase induction motors (§§ 689, 690), and 'universal' motors (*see below*). For special purposes D.C. motors with permanent magnet fields (§ 673), and synchronous motors (§ 680) are used in fractional-H.P. sizes.

The D.C. series type is restricted to applications in which it is desirable for the speed to decrease with increasing load, and to such purposes as driving fans so that there is no possibility of the load being completely removed, allowing the motor to race.

D.C. shunt motors are relatively constant-speed machines and their starting torque can be increased, if desired, by cumulative compounding, but this involves a greater drop in speed with increasing load unless the compound winding be disconnected after starting. In any case, the speed of shunt motors of fractional-H.P. decreases to a much greater extent than that of larger machines with increasing load; about 30 % decrease in speed between no-load and full-load may occur in D.C. shunt motors of $\frac{1}{10}$ - $\frac{1}{5}$ H.P. rating. Small shunt motors may be switched straight on to the supply, but a starter is advisable for motors larger than $\frac{1}{5}$ H.P. if the machine is to be started on load, or $\frac{1}{4}$ H.P. if the motor is to be started light.

Where a close approximation to constant speed is required, an induction motor may be preferable to a D.C. shunt motor, the decrease in speed of the former being usually about 8 or 10 % from no-load to full-load in fractional-H.P. sizes.

The efficiency of D.C. motors of fractional-H.P. is usually between 75 and 60 % (lower in the smaller sizes). The characteristics of small single-phase induction motors of various types are given in Table 122, § 690.

§ 710 ELECTRICAL ENGINEERING PRACTICE

Typical speeds and weights of fractional-H.P. motors are given in Table 127; lighter machines and motors of higher speeds can be obtained if desired.

TABLE 127.—*Typical Speeds and Weights of Fractional-H.P. Motors.*

Type.	Rating H.P.	R.P.M. (at 50 Cycles for A.C.).	Weight lb.
D.C. Series . . .	$\frac{1}{8}$ (0·020)	2 000	7 $\frac{1}{2}$
	$\frac{1}{4}$ (0·050)	2 400	15
D.C. Shunt . . .	$\frac{1}{8}$ (0·033)	2 000	11
	$\frac{3}{16}$ (0·050)	2 000	14
	$\frac{1}{4}$ (0·125)	1 650	20
	$\frac{3}{8}$ (0·167)	1 650	24
	$\frac{1}{2}$ (0·250)	1 650 / 1 000	36 / 60
	$\frac{3}{4}$ (0·500)	1 650 / 1 000	60 / 104
A.C. Series . . .	$\frac{1}{8}$ (0·020)	2 000	7 $\frac{1}{2}$
	$\frac{1}{4}$ (0·033)	2 000	11
	$\frac{3}{8}$ (0·050)	2 000	14
A.C. Induction (4-pole)	$\frac{1}{8}$ (0·125)	1 425	20
	$\frac{1}{4}$ (0·250)	1 425	38
	$\frac{3}{8}$ (0·500)	1 450	65

Small motors up to $\frac{1}{4}$ H.P. or so are largely used for driving domestic machines (§ 573, Vol. 2) *e.g.* vacuum cleaners, sewing machines, washing machines and refrigerators. The use per annum seldom exceeds more than 300-400 hours in the case of vacuum cleaners, sewing machines and washers, so that the total annual bill for their energy consumption is quite small, and the efficiency of the motor receives little consideration. On the other hand, where the motor is in service for long hours, as in the case of some small fans or blowers (particularly in industrial service) and in refrigerators, the total energy consumption is considerable, and it is worth while to purchase a motor of the highest efficiency available.

For example, a $\frac{1}{4}$ H.P. motor of 50 % efficiency consumes 373 W on full-load, whilst one of 70 % efficiency consumes only 266 W, a difference of 107 W which, during 2 000 hrs. per annum, and with energy at 1d. per kWh, represents a saving of 17s. 10d. on the electricity bill, or a return of 10 % on an investment of about £8 18s. In other words, there would be a net saving if the more efficient motor did not cost £8 18s. more to purchase than the less efficient machine.

The power factor of fractional horse-power A.C. motors is often very low and, where such machines are used in large numbers and for long hours, it is a matter of importance to the supply company

to encourage the use of those types of motors which have the highest power factor (§ 690). Taking a long view, the company should be equally interested in encouraging the adoption of the most efficient motors, the lower kWh consumption per motor being more than compensated by the increased use of electrically-driven appliances.

*'Universal' Motors.**—The term 'universal' motor is generally applied to a series-wound or compensated series-wound motor which is capable of operating at about the same speed and output on either D.C. or single-phase A.C. supply of about the same voltage and, in the case of A.C., of frequency not exceeding 60 cycles per sec.

As explained in § 700 any D.C. series-wound motor can, theoretically, be operated on single-phase A.C. supply and, though in the larger sizes there are material differences in the design and construction of motors intended for D.C. and A.C. operation respectively, it is both practicable and expedient to build small 'universal' motors of fractional horse-power, capable of being used satisfactorily on either D.C. or single-phase A.C. supply. All such motors are necessarily of the series type, because a D.C. shunt-wound motor cannot be operated on A.C. (§ 706), and the whole of the magnetic circuit must be laminated to avoid excessive eddy current loss when operating on A.C. supply.

In the earlier makes of universal motors there was a marked difference between the performances on D.C. and A.C. supply, and both the speed and the output were substantially lower, the higher the frequency of the A.C. supply. These differences have been largely overcome by improvements in materials and design, and the latest universal motors designed for high-speed operation, 3 500-4 000 r.p.m. and higher speeds up to 8 000 or 10 000 r.p.m., have torque-speed curves which vary 10 % or less from each other at all loads up to full-load on D.C. or A.C. between 25 and 60 cycles/sec.

The iron losses are heavier during A.C. operation, owing to the alternating flux in the field system; and the current is heavier, owing to the P.F. being relatively low. Both of these causes reduce the efficiency and the effective output. The main cause of the difference between the performances on D.C. and A.C. in the earlier machines was, however, the reactance voltage of the field windings, which increased with the frequency and was equivalent in effect to reducing the voltage applied to the motor. The seriousness of this factor has been reduced by designing motors to operate

* See § 424, Vol. 2 (5th Ed.), for motors which can be used on either A.C. or D.C. by means of grid-controlled mercury rectifiers.

with specially weak fields, a compensating winding being used where necessary to prevent the armature ampere-turns from distorting the field sufficiently to cause bad commutation.

Though a modern high-speed 'universal' motor justifies its name to the extent that it gives reasonably uniform performance on D.C. and A.C. supplies of frequencies from 25 to 60 cycles, the same cannot be said of low-speed machines or of the older makes of this type. There are still in use 'universal' motors which, on 50-cycle A.C. supply, are capable of developing only from one-third to two-thirds of their D.C. rating.

Universal motors, being series machines, are liable to run at dangerously high speeds on light loads except in the smallest sizes when the windage and bearing friction provide sufficient load to prevent the speed from rising unduly above the normal value, which is, itself, high in such cases.

Vacuum cleaners of the domestic type and portable drills are two of the commonest applications of universal motors; others are small fans, sewing machine motors, dish-washer motors, and in fact any machine requiring a high-speed motor of fractional H.P., provided that the series load-speed characteristic is not objectionable. Speed control can be obtained by variable series resistance, but it should be noted that this involves additional I^2R loss; also, the inherent decrease in speed with increasing load is accentuated because the voltage drop in the series resistance increases, and the voltage applied to the motor therefore decreases, with increasing load.

Within the usual limits of voltage variation, it may be assumed that the speed of a universal motor varies directly as the voltage.

711. Cost of Motors and Motor Control Gear.—The cost of electric motors varies considerably with the details of design and 'finish,' and very widely with the type of motor concerned (D.C., single-phase, polyphase, etc.), and with the speed of operation desired. Machines from a manufacturer's standard range are naturally much cheaper than those built to meet special requirements; for the majority of applications, it is possible to obtain a 'standard' machine meeting the requirements. A given carcass can be wound for a higher B.H.P. as the rotor speed is increased. This point is illustrated by Tables 115 and 119 (§§ 675, 681), in which the same weight appearing in different rows of the same column indicates the use of the same frame to develop different outputs at different speeds; naturally, the cost per H.P. is much lower

at the higher speeds; in fact the cost of the motor is determined mainly by the frame size employed and, within normal limits, varies only slightly with the voltage and speed for which that frame is wound. For example, a motor wound to develop 50 H.P. at 720 r.p.m. costs only about 10 % more than one wound for 10 H.P. at 110 r.p.m., the same frame being used in both cases. At any particular speed, the cost of a motor increases with the B.H.P. output but not in direct proportion; motors of fractional H.P. are relatively expensive, costing about £20 to £100 *per H.P.*, whereas 10 H.P. motors cost about £2 to £5 *per H.P.*, and 50 H.P. motors £1 10s. to £3 *per H.P.* for the usual ranges of speeds in each case. Where a wide range of speed control is required the cost of the motor may be increased by 15 or 20 %.

For the purposes of general estimates, the approximate list prices given in Tables 128 and 129 may be found useful. A number of firms specialise in the manufacture of standard motors by mass-production methods and are thus able to give extraordinary good value for money. In general, single-phase motors are considerably heavier and more expensive than polyphase motors of equal output, because a given frame can be wound for about double the H.P. with polyphase as compared with single-phase supply. For costs of fractional-H.P. motors *see also* Vol. 2, Table 76, § 573.

The price of motor control gear varies enormously with the type of gear concerned and with the details of design and manufacture. Here again, standardisation and mass production enable remarkably low prices to be quoted in some instances but, with this important exception, cheapness in motor control gear should be regarded with suspicion. As appropriate control gear alone enables full advantage to be taken of the possibilities of electric motors, it is very short-sighted policy to stint outlay thereon. The figures in Table 130 are list prices for first-class gear, and, in view of the multiplicity of parts, the accurate and substantial manufacture required, the delicacy of operation and the vital importance of reliability, it is not surprising that the control gear may cost considerably more than the motor itself, particularly in the case of low-power machines and where automatic operation of the control gear is required. The figures in Table 129 represent about the lowest prices for the simplest permissible starting gear, whereas those in Table 130 extend up to the more elaborate equipment. The higher cost of the latter is an excellent investment wherever use can be made of the fuller control thus provided.

TABLE 128.—*Approximate List Prices of D.C. and A.C. Motors: Fractional H.P.*

100/110 or 200/230 V.

Output.		D.C. Series and Compound Wound.		D.C. Shunt-Wound.		A.C. Series Commutator, 40/50 Cycles.		Universal Series Commutator, D.C. or A.C., 25-50 Cycles.		Single-Phase Induction, 50 Cycles.		A.C. Repulsion (Variable Speed) 50 Cycles.	
Watts (Approx.)	H.P. (Approx.)	R.P.M. (Full-Load).	Cost.	R.P.M. (Full-Load).	Cost.	R.P.M. (Full-Load).	Cost.	R.P.M. (Full-Load).	Cost.	R.P.M. (Full-Load).	Cost.	R.P.M. (Full-Load).	Cost.
15	$\frac{1}{8}$	—	£ s.	—	£ s.	—	£ s.	—	£ s.	—	£ s.	—	£ s.
20-25	$\frac{1}{4}$	2000	2 0	—	2 2	2000	2 2	2400	2 5	—	—	—	—
30-35	$\frac{3}{8}$	2000	2 12	2000	2 15	2000	2 15	—	—	—	—	—	—
45-50	$\frac{1}{2}$	—	—	—	—	—	—	—	—	—	—	—	—
70-75	$\frac{3}{4}$	2000	3 10	2000	3 15	2000	4 0	2400	4 3	1375	3 15	2700	7 0
90-95	$\frac{1}{2}$	1400-2300	4 10	1400-2300	4 10	—	—	2400	5 12	1400	4 5	2700	7 10
100-110	$\frac{1}{2}$	—	—	2000	4 12	2000	5 0	—	—	1400	5 10	2700	8 5
125	$\frac{1}{2}$	—	—	—	—	—	—	—	—	2500	5 0	—	—
150	$\frac{1}{2}$	—	—	—	—	—	—	—	—	2500	6 0	—	—
200	$\frac{1}{2}$	1400-2500	5 0	2000	5 10	2000	6 6	—	—	—	—	—	—
				2000	6 12	—	—	—	—	—	—	—	—

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TABLE 129.—*Approximate List Prices of D.C. Shunt-Wound and A.C. Induction Motors: 1-25 H.P.*
(see also Table 130).

Horse-Power.	R.P.M. (Approx.).	D.C. Shunt-wound; with Interpoles. 100/120; 200/240; or 400/480 V.				Single-Phase Induction. 200-400 V, 50 cycles/sec.				Three-Phase Induction.** 230-400 V, 50 cycles/sec.			
		Starter.*		Squirrel Cage.		Slip Ring.		Squirrel Cage.		Slip Ring.		Slip Ring.	
		Motor.	Starter.*	Motor.	Starter.	Motor.	Starter.	Motor.	Starter.	Motor.	Starter.	Motor.	Starter.
		£ s.	£ s.	£ s.	£ s.	£ s.	£ s.	£ s.	£ s.	£ s.	£ s.	£ s.	£ s.
1	1500	9 10	1 10	7 10	2 10	—	—	5 0	0 15	—	—	—	—
	900	12 0	1 15	9 10	2 10	—	—	6 5	0 15	—	—	—	—
	750	14 0	1 15	—	—	—	—	8 15	0 15	—	—	—	—
2	1500	12 0	2 0	10 10	3 0	—	—	6 15	1 5	9 5	—	3 10	—
	1000	14 0	2 0	13 0	3 0	17 0	8 0	8 15	1 5	11 0	—	3 10	—
	750	19 10	2 0	—	—	—	—	11 15	1 5	13 10	—	3 10	—
6	1500	19 10	3 15	21 10	5 10	—	—	10 10	1 5	13 15	—	6 15	—
	1200	25 10	3 15	—	—	—	—	—	—	—	—	—	—
	950	31 0	3 15	28 0	5 10	32 15	9 10	12 10	1 5	19 15	—	6 15	—
10	1500	31 0	4 10	—	—	—	—	16 15	4 5	19 10	—	7 5	—
	1100	36 10	4 10	—	—	—	—	—	—	—	—	—	—
	750	51 0	4 10	—	—	—	—	32 0	4 5	40 0	—	7 5	—
15	1500	36 10	6 15	—	—	46 0	15 0	—	—	27 0	—	7 15	—
	1100	45 15	6 15	—	—	—	—	—	—	—	—	—	—
	950	52 0	6 15	—	—	57 10	15 0	—	—	—	—	—	—
20	1500	63 0	6 15	—	—	—	—	—	—	50 0	—	7 15	—
	1430	51 10	8 10	—	—	57 0	18 0	—	—	33 10	—	8 10	—
	940	63 10	8 10	—	—	83 0	18 0	—	—	42 0	—	8 10	—
25	1500	79 0	8 10	—	—	—	—	—	—	59 0	—	12 10	—
	1060	63 10	10 0	—	—	—	—	—	—	50 0	—	12 15	—
	850	78 0	12 0	—	—	—	—	—	—	—	—	—	—

* Above 5 H.P., add 25% for 100/120 V.

** Add about 10% to price for 2-phase motors.

TABLE 130.—*Approximate List Prices of D.C. and A.C. Motor Starters of First-Class Manufacture.*

Motor Voltage and H.P.	Direct Current.			Alternating Current.		
	Hand- Operated Face- Plate Starter : no Switches or Fuses.*	Hand- Operated Drum- Type with Main Contactors and Shunt Regulator.	Automatic Solenoid or Contact Type with Shunt Regulator.	Hand- Operated Straight-on Type. Air Break or Oil Immersed.	Hand- Operated Star-Delta, Air Break or Oil Immersed.	Hand- Operated Trans- former Type, Oil Immersed, or, Hand- Operated Rotor Starter, Oil Immersed.
100-250 V	£ 1-3 5-10	£. 20-30 30-45	£ 44-50 50-70	£ 9-12 10-15	£ 10-15 11-15	£ 25-28 26-26
				£ 20-22 22-25	£ 20-22 22-25	£ 44-50 45-60
200-550 V	£ 15-20 50	£. 40-50 65-75	£ 90-70 95	£ 14-18 —	£ 15-20 17-25	£ 26-34 30-50
			£ 130-150	£ 24-32 32-42	£ 24-32 32-42	£ 50-50 75-100
400-650 V	—	100	—	—	23-25	44-55
			1-0	45	23-25	90-120
						130-140

* About twice these figures if complete with main switch, fuses and shunt regulator.

712. Bibliography.—(See explanatory notes, § 58, Vol. 1.)

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See Chapter 41 in this volume.

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- (1) *Government Department Electrical Specifications (H.M. Stationery Office).*

No. 2.—Direct Current Motors from 1 to 100 B.H.P. (Open and totally enclosed types for continuous service, and short time rated).

No. 15.—Alternating Current Motors (Induction Type).

- (2) *I.E.C. Publications.*

No. 34.—Rules for Electrical Machinery.

- (3) *British Standard Specifications.*

No. 96.—Parallel Sided Carbon Brushes for D.C. Commutator Machines.

No. 168.—Electrical Performance of Industrial Electric Motors and Generators.

No. 169.—Electrical Performance of large Electric Generators and Motors. Rating permitting overloads.

No. 170.—Electrical Performance of Fractional Horse-Power Electric Motors.

No. 173.—Electrical Performance of D.C. Series-Wound Traction Motors.

No. 226.—Electrical Performance of large Electric Generators and Motors. Continuous maximum rating.

No. 229.—Flame-Proof Enclosures for Electrical Apparatus and Tests for Flame-Proof Enclosures.

No. 269.—Methods of Declaring Efficiency of Electrical Machinery (excluding Traction Motors).

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 The Two-Speed Cascade Induction Motor, A. H. M. Arnold. Vol. 63, p. 1115.
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 Variable Speed A.C. Motors without Commutators, F. Creedy. Vol. 61, p. 309.
 The Circle Diagram of the Induction Motor, L. H. A. Carr. Vol. 66, p. 1174.
 The Circle Diagram of the Polyphase Induction Motor, C. C. Hawkins. Vol. 69, p. 1149.
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 Single and Three-phase A.C. Commutator Motors with Series and Shunt Characteristics, S. P. Smith. Vol. 60, p. 308.
 Test Results from a Three-Phase Shunt Commutator Motor, F. J. Teago. Vol. 60, p. 328.
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MISCELLANEOUS.

- Tables and Diagrams for Reconnecting 3-ph. Induction Motors.
 A. C. Roe, *Electrical World*, July 24, 1920.
 Ditto for Two-Phase Induction Motors, *ibid.*, October 2, 1920.
 Handbook of the Electric Power Club (U.S.A.).

NOTE.—While this book was in the press, D. B. Hoseason announced in a paper before the Manchester Association of Engineers (*Electrician*, Vol. 110, p. 167) that insulating the bars of a squirrel-cage motor does not increase the heating. On the contrary, the temperatures of the rotor and stator, and of the outlet air, are all reduced by insulating the bars. This may correspond to 2 or 3 per cent. increase in motor efficiency; and it seems probable that the true efficiency of most squirrel-cage motors with bare bars is 2 or 3 per cent. below the declared value, as the latter generally does not allow for stray-load losses.

MOTOR CONTROL.

713. Control and Protection of Electric Motors.—Every electric motor must be provided with means for starting and stopping its rotation and, in many instances, provision must be made for speed control. The simplest method of starting is by switching the machine straight on to the supply mains, but this is only permissible in the case of motors which have self-starting characteristics, and then only in D.C. motors of fractional horse-power, and in certain types of A.C. motors, notably induction motors of moderate size and some types of A.C. commutator motors. In general, the rush of current and the mechanical shock at starting must be kept within limits by using a series resistance, auto-transformer or other means of reducing the applied voltage, or by some such device as brush-shifting. Speed control may be effected by varying one or more of the factors which determine the speed of the machine, *e.g.* field strength, applied voltage, frequency, brush-setting, etc., as the case may be. The simplest method of stopping is to disconnect the supply and allow the motor to be retarded by its load, or simply by frictional resistance. Sometimes, however, braking may be applied to obtain increased retardation and more rapid stopping or, by regenerative braking, some recovery of the energy stored in the moving parts. Though they are not, perhaps, part of the 'control' gear in the ordinary sense of the term, such protective devices as may be necessary to safeguard motors against overload and against direct application of full-voltage after temporary failure of supply are arranged to operate the control gear in a manner bringing about the desired result.

The preceding remarks apply broadly to every electric motor, and the particular requirements and characteristics of individual types are discussed in later paragraphs. British standard definitions relating to motor starters and controllers are summarised in § 719;

and the components, construction and operation of a typical range of starters and controllers are dealt with in § 738.

The purpose of a *starter* is to provide for the acceleration of the motor from rest to normal speed under acceptable conditions both as regards rate of acceleration and magnitude of current during the period of starting. A *controller* provides for regulation of the speed during the working period, and for reversal if required, as well as for starting the machine. It is, of course, necessary to discriminate between the inherent speed variation of the motor with changing load and the control of speed by external means. Sometimes the speed has to be controlled to compensate for an inherent tendency to vary with load and, in all cases, the speed set by a controller is subject to the inherent speed regulation* of the machine which may be large as in the D.C. series motor, or zero as in the A.C. synchronous motor.

The potential advantages of electric driving, in point of range and flexibility of speed control, can only be realised by using appropriate control gear. The correct choice of motor starters and controllers is, in fact, as important as the selection of the motors themselves. Each type of motor requires certain operations to be performed in order to start the machine and alter its running speed, *e.g.* variation of applied voltage, variation of field strength, change of connections between windings, and so on. These operations are broadly the same for each particular type of motor, but the success of the drive depends essentially upon the operations of starting and control being adapted (both as regards mechanism and timing) to the particular requirements of the load. In other words, the mechanical characteristics of the load, as well as the electrical characteristics of the motor, must be taken into consideration when choosing the control gear. The use of automatic control gear is advantageous from both of these standpoints. On pressing one

* The 'speed regulation' of a motor may be defined as the percentage rise in speed between full-load and no-load, referred to the full-load speed, the conditions of supply and the motor connections, field regulator, etc., remaining constant (*cf.* 'voltage regulation,' § 147, Vol. 1). There is no connection or relation between the speed regulation of a motor and its adaptability to speed control. The speed regulation may be very 'stiff,' nearly zero, yet the motor may be capable of speed control over a wide range; the D.C. shunt motor is a case in point. On the other hand, the speed regulation may be high, as in an A.C. induction motor with a high-resistance rotor, yet no provision may be made for speed control. The inherent speed-regulation characteristics of various motors are dealt with in Chap. 28.

button, the motor is started by means of a solenoid or contactor type starter, at the maximum rate of acceleration permissible in the service concerned. 'Stop' buttons placed in convenient positions enable the motor to be stopped quickly in case of emergency. Speed adjustment is usually effected by hand-regulation, but where the speed has to be changed from one to another of several definite values it is an easy matter to arrange press-button control for the purpose. Again, a manually or automatically operated drum controller enables even the most intricate series of changes in connections to be effected in correct sequence and timing. Instances could be multiplied indefinitely, but the main points which it is desired to emphasise are that: (1) the control gear is a vital part of the driving equipment; and (2) automatic or semi-automatic operation is often a good investment.

714. Starting Conditions.—The rate of acceleration of a motor and the duration of the heavy starting-current flow are determined by the magnitude of the latter, the starting torque of the motor, and the inertia of the motor and its coupled load. In this connection, the starting torque developed by the motor per ampere of starting current is a useful figure for purposes of comparison. The starter should be electrically and thermally capable of starting the motor on the maximum load against which the motor is required to be started; if this is not the maximum load against which the motor is capable of starting, it will be necessary to provide a starter of larger capacity if the motor is applied to a heavier load.

The torque applied to the load is increased by the use of speed-reduction gearing, as employed with high-speed motors; this may be an advantage or a disadvantage at starting according to the nature of the load and the method of starting. If the load is driven through a magnetic or friction clutch, a starting torque can be applied to it equal to the maximum running torque which the motor, already running at full speed, is capable of developing. This is the stalling or pull-out torque of the motor and, in general, the motor (unless it is a synchronous machine) will slow down in developing it. The current required for starting by this method is only equal to that taken by the motor to develop this running torque. In some instances the torque which can be applied to the load by this method is greater and the current required is less than when starting the motor from rest, direct-coupled to the load.

As explained more fully in § 749, it is important that the

characteristics of the motor should suit those of the load under all conditions of operation. In so far as the motor characteristics during starting and speed regulation are concerned, this is to some extent a matter of control, though the inherent characteristics of the motor are of primary importance.

The expressions 'full-load' and 'full-load torque' are often used carelessly. A motor which has to start against full-load, *e.g.* a traction motor or a motor coupled to a grinding mill left full of material, may have to develop a starting torque equal to 3 or 4 times the normal full-load torque. On the other hand, a motor which has only to develop full-load torque on starting is on comparatively easy duty, for the torque required will almost certainly fall well below full-load value directly the machine is in motion.

Misunderstanding often arises from the statement that a particular motor develops a certain starting torque (usually expressed as a fraction or multiple of the full-load torque) with a certain starting current (similarly expressed in terms of the full-load current). At the moment of switching-on the current is determined by the impedance of the windings and the E.M.F. applied to the latter, there being no back-E.M.F. at this moment. This is the current which develops a certain starting torque as stated above, but the subsequent course of events depends entirely on the relation between the torque developed by the motor and that required by the load as the speed increases. If the motor is driving no load it accelerates rapidly, but if it is connected to a load which requires the full starting-torque of the motor to set it in motion there may be only a small margin of torque available for subsequent acceleration. If the torque developed by the motor decreases during the early stages of acceleration (*see*, for example, Fig. 278, § 684), it is conceivable that it may be inadequate to accelerate the load beyond a certain low speed at which the torque demanded by the load *excluding* acceleration equals the torque developed by the motor. This difficulty could be overcome, in the case of a squirrel-cage induction motor started by means of a compensator, by using a higher voltage tapping on the latter. In the case of D.C. motors, the remedy would be to increase the field strength.

715. Methods of Braking.—In many applications there is no need to make any provision for braking electric motors; in such cases the machine is simply disconnected from the supply and allowed to run, free or still coupled to its load, until it is brought

to rest by windage, bearing friction and other forms of mechanical resistance. It may, however, be necessary to bring the motor and its load to rest quickly either as a matter of convenience or for reasons of safety. Such cases arise in traction service (§ 899), in machine tools, printing and other machines, in flywheel storage sets, and so on. Mechanical brakes offer one means of increasing the retardation or deceleration by adding to the frictional resistance to be overcome.

'Electrodynamic' braking effects the same result by converting the stored kinetic energy of the motor, and its load if coupled, to electrical energy which is dissipated thermally as I^2R loss in a suitable resistance. For this purpose the motor is arranged to act as a generator, driven by its own inertia and that of any coupled load. The whole of the stored energy is dissipated as heat (some by mechanical friction in bearings, etc., but most by electrical I^2R losses), but there are no brake blocks to be provided and maintained if the electrical energy is dissipated in plain resistances. Combined mechanical and electrodynamic braking may be effected by utilising the electrical output from the motor, acting as a generator, to excite the windings of magnetically actuated mechanical brakes. Though electrodynamic action can provide powerful braking it cannot 'hold' a stationary load, because the motor no longer generates current when it is stationary; in practice it ceases to generate any useful amount of current before it actually comes to rest. The degree of electrodynamic braking can be controlled by varying the resistance through which the terminals of the generating motor are connected, maximum effect being produced when the terminals are short-circuited. In most cases the current then flowing would be excessive when the motor was at or near full speed. More or less resistance is therefore required at first, and this may be decreased, with or without simultaneous increase in field strength, in order to maintain a powerful braking effect until the motor comes nearly to rest or ceases to be self-exciting. Whilst it cannot hold a stationary load, electrodynamic braking is an effective safeguard against an 'overtaking' load running away with or racing the motor.

Some loads, such as those of cranes and hoists, must be held continually when they are not being driven. In such cases clapper brakes applied by springs, gravity-actuated brakes, or other equivalent types may be employed, the brake being taken 'off' by the

pull of an electromagnet, which is excited only when the motor is carrying at least a predetermined minimum current.

The principle of electrodynamic braking at once suggests the possibility of 'regenerative' braking, *i.e.* the returning of the electrical output from the inertia-driven or load-driven motor, acting as a generator, to the supply mains or to some other circuit in which it can be utilised instead of being merely dissipated as heat. Obviously, regenerative braking is most applicable to such a case as that of a train running on a down-grade, where retardation is required for a more or less considerable period, the motor continuing to run at a reasonably high speed, and the amount of energy involved being so considerable as to justify the expense and complication of recovering it. The method is also applicable to tramcar control, recent (1931) tests showing that 20 to 30 % saving of energy can be effected by regenerative control equipment, even when operating partly in city districts with frequent stops and on routes which are not hilly.* Better results are obtained on hilly inter-urban routes where infrequent stops make possible a higher schedule speed. On such routes, however, the service is generally light and trouble may arise from the feeding back of current from a single car to a rotary converter or automatic sub-station.

Regenerative braking is used to some extent in these and similar applications, *e.g.* colliery winding, but, like simple electrodynamic braking, it cannot be used to stop and 'hold' the load, and it is only feasible when the voltage and (if A.C.) frequency of the 'regenerated' current can easily be held constant at the appropriate values, regardless of variations in the speed of the motor. Regenerative braking is practicable with D.C. motors down to relatively low speeds, as long as the field can be increased sufficiently to keep the E.M.F. generated by the motor above the voltage of supply,† but it is limited to speeds above the normal in the case of induction motors. The use of ordinary electrodynamic braking, with I^2R dissipation of energy, is not restricted by any considerations of the voltage or frequency of the current generated.

In some instances, particularly in the case of auxiliary motors in steel mills, the retardation and reversal of motors is hastened by applying reversed E.M.F. whilst the armature or rotor is still

* See also *El. Rev.*, Vol. 112, p. 340.

† This voltage itself can be reduced when the motor is supplied from a Ward-Leonard set or other variable-voltage source.

running in the forward direction. This operation is called 'plugging' the machine. In the case of a D.C. motor, in order to prevent the current from rising to an abnormal value at the moment of plugging, when the back-E.M.F. of the forward-running armature aids the reversed applied E.M.F., additional resistance is connected temporarily in series with the armature, over and above that required when starting in either direction from standstill. For example, if R be the series resistance which limits the current to full-load value at the moment of starting from rest, $\frac{2}{3}R$ may be placed in series with the armature when plugging the motor, and $\frac{1}{2}R$ when starting from rest. 'Plugging' an A.C. motor is effected by reversing the phase rotation of the applied voltage. The slip is then twice that corresponding to the supply frequency, and decreases to that corresponding to the supply frequency as the rotor comes to rest. When the speed reaches zero, the power supply must be disconnected to prevent reversal of rotation; this involves complications in the control equipment. Neither 'plugging' nor electrodynamic braking is capable of holding a machine stationary. The disturbance to the supply circuit conditions is liable to be serious when 'plugging' is employed; and more rapid stopping can generally be effected by electrodynamic braking (*see also* § 722).

716. Control of D.C. Motors: General.—As explained in § 669, it is usually necessary to connect external resistance in series with a D.C. motor at starting, in order to limit the magnitude of the current flowing. The calculation of suitable values for a subdivision of the starting resistance is discussed in § 719.

The running speed of any particular D.C. motor under steady load being determined by the voltage applied to the armature and the degree of excitation of the field windings (§ 669), the speed may be varied by voltage control, by field control, or by a combination of both methods.

Where field control is used, practically constant H.P. can be developed at all speeds, the torque increasing as the speed decreases. It is obvious, however, that a motor which is capable of developing its full H.P. at low speeds must be utilized imperfectly at higher speeds; in other words, it is heavier than a constant-speed motor capable of developing the same H.P. at the higher speed. In the voltage control method, the field and the armature current remain constant over the whole range of speed; the torque is therefore constant and the H.P. varies with the speed. The material in the

motor is utilised efficiently at all speeds, but special provision must be made to secure variable-voltage supply without undue dissipation of energy.

Speed Variation by 'Field Control.' Moderate speed variation can be obtained in a shunt-wound motor by the use of a variable resistance in series with the field windings (Fig. 324); this field-regulator or shunt resistance must not be confused with the starting resistance which is placed in series with the armature (*see* Fig. 328, § 717). As extra resistance is inserted in the field circuit the current in the latter is reduced, the voltage applied to the terminals being constant; the magnetic field is therefore weakened and the armature

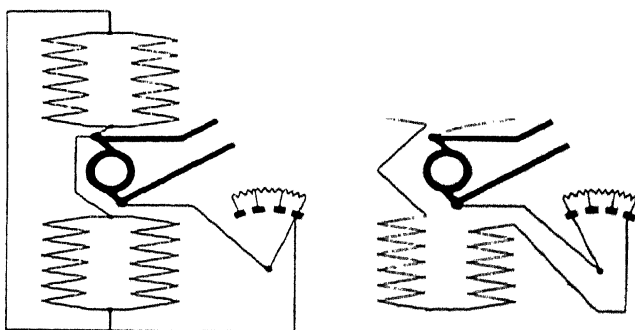


FIG. 324.—Speed variation by field control (D.C. shunt-wound motor). In the left-hand diagram the field coils are in parallel and the shunt (field-regulator) resistance is out; in the other case, the windings are in series and the shunt resistance in.

has to revolve more rapidly in order to generate the required back-E.M.F. In modern motors, with interpoles to maintain good commutation, a speed range of 3 : 1 can be obtained fairly easily by field control, and a range of 5 or 6 : 1 can be obtained if specially required. Changing the connection of pairs or groups of field coils from parallel to series, as in Fig. 324, is equivalent to inserting resistance in series with the winding; in the case illustrated, the field current with all four coils in series would be one-quarter of that with the coils connected in pairs in parallel and the two groups in series. This method of field control does not alone provide a fine gradation of speed, but, in conjunction with variable field resistance, it is useful in some special applications, *e.g.* electric vehicle motors (§ 945).

The speed of D.C. series motors may be varied by means of a variable 'diverter' resistance in parallel with the field coils, but the speed control thus obtained is not stable.

Speed Variation by 'Voltage Control.'—This method is used extensively where a wide range of speed control is desired, *e.g.* for motors driving printing presses, rolling mills, winding gear, etc. As long as the field is kept constant, the torque corresponding to a certain armature current is also constant; varying the voltage applied to the armature changes the speed, and the H.P. of the motor varies with the speed.

It is inefficient to regulate the armature volts by series resistance, but this method is used on grounds of expediency in small fan motors and for occasional intermittent use with series motors. Series-parallel control of the latter is one form of variable voltage control, and is particularly useful in traction and similar work. A given series resistance causes more or less pressure drop as the current flowing increases or decreases, so that speed regulation thus obtained is not stable but varies with load.

A more efficient and convenient method is to place a motor generator set between the mains (D.C. or A.C.) and the D.C. motor controlled. By varying the speed and the generator field of the motor-generator any pressure from a positive to a negative maximum can be applied to the motor controlled, and the speed of the latter thus varied from standstill to maximum in either direction. This is the Ward-Leonard system of control. Its chief disadvantage is that three machines are required instead of one, each of the auxiliary machines being as large as the main motor, since they carry the whole supply to the latter. This makes the system expensive in first cost where small power applications are concerned, but for high-power variable-speed drives the Ward-Leonard equipment is little if any more costly than a single D.C. motor, with the control gear needed to obtain suitable variation of speed, and the proportionate share of the D.C. generating or converting plant.

The Ward-Leonard equipment as used extensively in connection with rolling mills, colliery winding gear, and other heavy drives, consists generally of a shunt-wound D.C. motor connected permanently to the terminals of a shunt-wound D.C. generator, the latter being driven by a motor (usually a 3-phase machine) supplied from the mains. The D.C. motor is separately excited from a constant-voltage supply, with or without a shunt regulator in the field circuit.

The generator is also separately excited, with provision for varying the voltage applied to its field from zero to a maximum in either direction. The voltage applied to the motor armature can thus be varied from zero to a maximum in either direction and the machine runs at any speed from zero to maximum forwards or reverse with constant torque for given current. The I^2R losses being constant for given current, and the H.P. varying directly with the speed, the efficiency is low at low speeds. In a typical case the overall efficiency was about 82 % at full speed, about 71 % at half speed, and lower at lower speeds. As there is no rheostatic control in the main circuit there is no supplementary I^2R loss during starting and acceleration. Also regenerative braking can be effected by weakening the generator field; the kinetic energy of the motor and load

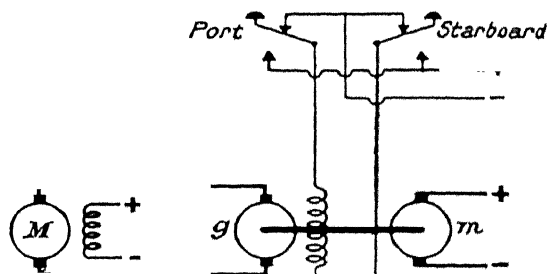


FIG. 325.—Ward-Leonard set without provision for speed control.

then drives the generator as a motor and causes the motor of the motor-generator set to feed energy back to the mains. The saving of energy during acceleration and retardation is an important factor where the load has to be started and stopped frequently. On the other hand, the light-load and windage losses of the motor-generator set are continuous, this set generally running throughout the shift.

The general arrangement of a Ward-Leonard set is shown in the upper part of Fig. 362, § 729. A simpler arrangement for reversible driving without provision for speed control is shown in Fig. 325, as used to operate the electrical steering gear of a ship by press buttons for port and starboard respectively. According to which button is pressed, the field of the generator in the motor-generator set m - g is excited in one direction or the other, and the rudder motor M runs forwards or backwards.

Where, as in colliery winding, it is desired that the position of

the control lever regulating the field of the variable-voltage dynamo should correspond to a definite speed of the motor, the dynamo must be compounded. Referring to Fig. 326, the dynamo D is excited by an auxiliary machine g , which is itself a compound-wound machine with: (i) a shunt winding a , excited at variable voltage, plus or minus, by tappings from the potentiometer rheostat r ; and (ii) a series winding b , excited by the P.D. (= ohmic voltage drop) in one of the leads between D and M , or in a special resistance inserted in this lead for the purpose. When M is running as a motor the winding b aids a ; and the dynamo D is thus compounded to such an extent that the voltage on the terminals of M remains constant for a given setting of r whatever the load on the set. On the other hand, when M is driven as a generator by a descending load, the voltage drop between M and D is reversed, hence b opposes a , and the E.M.F. of D is reduced to such an extent that M still runs at the same speed for a given setting of r .

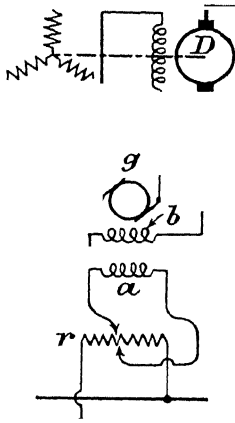


FIG. 326.—Ward-Leonard set with compounded dynamo.

In the Brown-Boveri equipment, as actually built for operation on this principle, the exciter g , Fig. 326, and the exciter for M are driven by an auxiliary motor, so as to be independent of the speed variations of the converter set. Also, the field b is a shunt winding excited from a potentiometer rheostat (which compensates for the saturation curve of the dynamo) through a variable rheostat which is adjusted automatically by a moving-coil device connected across a shunt in one lead between D and M . A further refinement consists in an automatic adjustment of the rate of retardation to suit the direction and magnitude of the torque of the load, so that the cage comes to rest at the correct level whatever the load; a wattmeter element inserts a resistance in the excitation circuit sooner or later according to the magnitude and direction of the load. These are details important in practice but not affecting the principle of the control.

For small or moderate power applications, a method more economical than the Ward-Leonard system in first and running costs consists in connecting the two machines of a mechanically

coupled motor-generator set electrically in series across the supply mains, the main motor which it is desired to control being then connected across the terminals of the generator in the auxiliary set. This system is particularly useful where the voltage reduction required is relatively small. In the Ward-Leonard system the motor and the generator of the regulating set have each to deal with the whole load. In the method now considered, neglecting losses, the auxiliary generator has to deal with ei_v watts, where e = reduced voltage applied to the main motor, and i_v = difference between main motor current I and current taken from the mains i_m ; while the auxiliary motor has to deal with $(E - e)$ volts and $(I - i_v)$ amperes, where E = main supply voltage. Neglecting losses, the capacity of each of the auxiliary machines is $ei_v + (E - e)(I - i_v)$ watts, and is smaller the smaller the voltage reduction $(E - e)$. Under these conditions, the auxiliary generator deals with small current and nearly the mains voltage, while the auxiliary motor deals with low voltage and nearly the full current of the main motor.

The use of boosters as a means of obtaining variable voltage supply is explained in § 389, Vol. 2.

Multi-voltage control can, however, be practised without the use of a motor-generator or booster giving continuous gradation of voltage. In the 3-wire system of distribution, say at 440 / 220 V, the field circuit of a shunt motor may be connected across the 440 V 'outers,' and two speeds then obtained without control losses by connecting the armature between an 'outer' and 'inner' conductor (220 V) or between the two 'outers' (440 V).

Greater flexibility of control is obtained if the pressure between the outers be divided unequally, either by taking suitable tappings from the generator armature or by running motors wound for, say, 90 V and 160 V in series across a 250 V supply and taking a 'neutral' third-wire from the common terminal of these machines. In a 90 / 160 / 250 V, 3-wire system, there are eight control stages available, viz.: (1) Field across 250 V lines, armature across 90 V lines; (2) Field resistance inserted till speed approaches that for stage (3), which consists in connecting the armature through resistance, across 160 V lines, and removing field resistance; (3) Armature straight across 160 V, field across 250 V; (4) Field resistance inserted till speed approaches that for stage (5), which consists in connecting armature through resistance across 250 V, field resistance being simultaneously removed; (5) Armature and field directly on 250 V supply; (6) Armature on 250 V, all field resistance in; this is the maximum speed. There are no control losses in stages 1, 4, and 7 of this schedule. In stages 2, 5, and 8 there is a certain, very small loss in field regulation; and in stages 3 and 6 there is a more serious loss in the resistance connected in series with the armature, but these stages may be made to correspond

to transitory, accelerating notches on the controller, and not used for running speeds. By further subdividing the supply voltage, say, to 60, 80, and 110 V (requiring four distributing cables) very finely subdivided and efficient control is obtained.

717. Starting and Speed Control of D.C. Shunt-Wound Motors.—Generally, the control gear for a shunt-wound D.C. motor includes a resistance connected in series with the armature during the starting period, this resistance being progressively removed as the machine accelerates; and a variable resistance for weakening the field when it is desired to run at higher than normal speed. As noted later, there are methods of varying the speed of shunt motors other than by field resistance, but these methods are only applicable to special cases.

STARTING.—Small shunt-wound motors up to $\frac{1}{2}$ or $\frac{3}{4}$ H.P. can

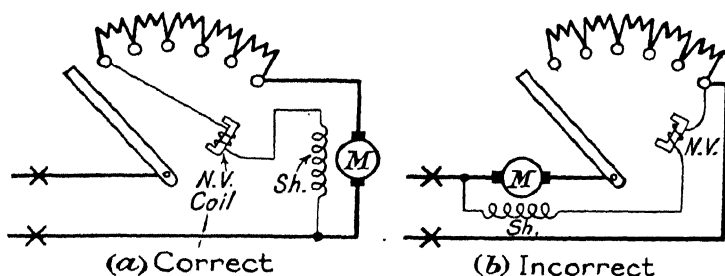


FIG. 327.—Illustrating correct and incorrect connections for shunt field circuit.

generally be started on no-load by switching them straight on to the mains, but whenever the inertia of either the motor or its load is sufficient to cause any appreciable delay in reaching full speed a starting resistance must be used, otherwise the heavy current flowing through the armature will at least blow the fuses and will probably damage the commutator and the insulation of the windings.

In any case, shunt motors should be started on 'full field,' *i.e.* with no external resistance in the field circuit. This is ensured by connecting one terminal of the field winding to the negative terminal of the armature, and the other to the *first* contact of the starter (see Fig. 327 (a)). This arrangement has the further advantage that it provides a shunt circuit (*via* the starting resistance and armature) through which the shunt field can discharge when the main circuit is opened whether by the starter arm or the main

switch; unless such a path is provided, the inductive 'kick' when the shunt field circuit is broken will cause heavy arcing and may break down the insulation of the windings. The field connection shown in Fig. 327 (*b*) also secures full excitation at starting, but does not provide a path for the discharge of the field and should therefore not be employed. Another objection to the arrangement in Fig. 327 (*b*) is that the field and no-volt coil are in circuit as long as the main switch is closed, even if the starter be 'off.' Unless the shunt field regulator (for speed control) is of low resistance, say limited to 10 % speed variation, a relay or an interlocking device is used to ensure that the regulator is in the full field position before the motor can be started (§ 738). An auxiliary brush on the starter arm is sometimes provided, bearing on a sector contact connected to the first stud of the starter; this maintains full field throughout the starting period.

With full field, the D.C. shunt motor develops full-load starting torque with full-load current, *i.e.* when the armature current equals the full-load value. The actual value of the armature current at starting is determined by the value of the starting resistance and by the resisting torque of the load. Until the armature begins to rotate, the current flowing is determined by the resistance of the armature plus that of the starting resistance in circuit; and the armature will not begin to rotate until the current reaches such a value that the torque of the motor exceeds the resisting torque of the load. The field being constant, the torque varies directly with the armature current.

SPEED CONTROL.—The speed of a D.C. shunt-wound motor may be varied by field or armature control or by a combination of these methods. *Field control* may be effected by placing more or less resistance in series with the field windings (*see* Fig. 328), thus decreasing or increasing the strength of the field. The weaker the field the higher must be the armature speed to generate the requisite back-E.M.F. (*see also* § 669). Field control is the most economical method of regulating the speed of a shunt-wound D.C. motor. It is applicable only to obtaining speeds *above* the speed corresponding to full-field (*i.e.* no external resistance in series with the field). The insertion of resistance in series with the field reduces the current and therefore the total expenditure of power in the field circuit; and as the excitation of the field seldom demands more than 3 or 4 % of the total input to a shunt motor, it is evident that the

power dissipated in the field-regulating resistance is practically negligible.

For what is nominally a constant-speed drive, it is usual to provide a field rheostat making possible about 10 % variation in speed, so that the r.p.m. of the driven machine can be adjusted to the exact value desired.* A much wider range of speed control can be obtained, if desired, by means of field regulation. Thus, a 3 or 4 or even 6 to 1 speed-range is obtainable by varying the resistance in series with the field windings, but in such cases interpoles are essential to maintain satisfactory commutation notwithstanding the large variations in the strength of the main field, and a light series

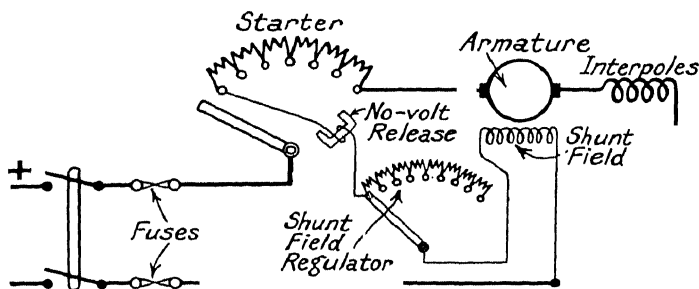


FIG. 328. —Diagrammatic representation of D.C. shunt motor starter and shunt field regulator.

field is generally added to ensure stability of running on fluctuating loads at high speeds, when the shunt field is of course weak.

Very fine adjustment of speed can be obtained by using coarse- and fine-adjustment field rheostats in series. If, for example, the coarse-adjustment rheostat be divided into ten equal parts, and if the fine-adjustment rheostat (equal in total value to one of the ten divisions of the coarse rheostat) be also divided into ten equal parts, then 101 speed settings are available.

* Usually the field rheostat in such cases provides for 10 % increases (up to 25 % if required) above the rated r.p.m. of the motor. If, however, it is desired to provide for speed adjustment on each side of a normal or rated r.p.m., it is evident that the motor must normally be operated with some external resistance in series with the field; in other words, part of the field rheostat must normally be 'in,' and the I^2R loss therein will slightly reduce the efficiency of the motor. Then by reducing or increasing the amount of resistance in series with the field winding the motor speed can be lowered or raised.

Armature control of the speed of a shunt-wound D.C. motor is effected by varying the E.M.F. applied to the armature terminals. This may be effected by supplying the motor from a special generator, the voltage of which is varied as required, the motor field meanwhile being kept constant by exciting it from an independent constant-voltage supply (§ 674). This arrangement, which constitutes the Ward-Leonard control (§ 716), gives stable regulation, *i.e.* the speed of the motor is practically independent of load; also, the method is efficient, there being no appreciable regulation losses other than the losses in the generator. A variation of this method is to supply the armature from a multi-voltage system, *e.g.* a 3-wire 220 / 440 V system, a 5-wire 110 / 220 / 330 / 440 V system, and

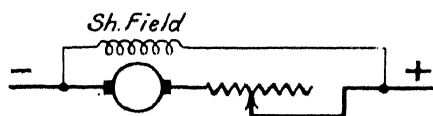


FIG. 329.—Diagrammatic representation of speed control of D.C. shunt motor by resistance in armature circuit.

so on. This method only provides for a certain number of definite speeds, in the same ratios as the available supply voltages; the control is stable and efficient as regards the avoidance of regulation losses but a multi-

voltage distribution is complex and costly and does not provide for continuous variation of speed.

As generally understood, armature control involves the use of external resistance in series with the armature, the field being excited at full voltage all the time (see Fig. 329). This method is applicable only to obtaining speeds *below* that corresponding to full voltage on the armature (*i.e.* no external resistance in series with the armature); and it is particularly applicable to the obtaining of 'inching' or 'creeping' speeds, such as are required when preparing the driven machine for work. The IR pressure drop in the series resistance reduces the available E.M.F. at the terminals of the armature, but as the regulating resistance carries the full current of the armature there is a serious waste of energy. Also, the IR drop in the resistance varies with I , *i.e.* with the load on the motor, hence the decrease in speed produced by a given resistance in series with the armature increases with the load on the motor. Speed control of a motor by resistance in the armature circuit is neither efficient nor stable. The importance of the loss in the regulating resistance depends, however, on whether the load demands constant torque or whether the power required falls more

rapidly than the speed; this point is illustrated by the following examples :—

EXAMPLES.—Taking the case of the 50 H.P., 500 V, 400 r.p.m., shunt-wound D.C. motor mentioned in § 669, the armature current is 57·5 A when the machine is running at 400 r.p.m. with 500 V supply. The relation between the applied E.M.F. E , the back-E.M.F. E_b , and the pressure drop $e (= IR)$ in the armature is : $E - E_b = e$; which in the present case gives : $500 - 488·5 = 11·5$ (see worked example in § 669).

Suppose now that the motor is driving : (a) A load of constant torque ; (b) a fan, the H.P. of which varies approximately with the cube of the speed.

Case (a). Constant Torque.—The field being constant (by hypothesis), the armature current must also be constant, to develop the constant torque. The pressure drop e is therefore constant and, if the applied E.M.F. E be halved, we have

$$\begin{aligned}\frac{1}{2} \cdot 500 - E_b &= 11·5, \\ \text{whence } E_b &= 238·5 \text{ volts.}\end{aligned}$$

At 400 r.p.m. $E_b = 488·5$ volts, hence, the field being constant, the speed is now $400 \times 238·5 / 488·5$ or 196 r.p.m. In other words, the speed is slightly more than halved by halving the voltage applied to the armature.

If the voltage across the armature is halved by series resistance the pressure drop in the latter must be 250 V, and, the armature current being 57·5 A, the necessary resistance is $R = 250 / 57·5 = 4·35 \Omega$.

Obviously the power dissipated in the series resistance ($= 250 \times 57·5 W$) is equal to the power input to the armature. In other words, the total input to the armature circuit (armature plus series resistance) is still $500 \times 57·5 W$ or the same as at full speed, but the B.H.P. of the motor at half speed and constant torque is only half the full-speed H.P. The efficiency of the motor at half-speed is therefore half the full-speed value.* Clearly, speed regulation by series resistance in the armature circuit is very inefficient where a constant torque load is concerned.

Case (b). Fan Load.—In this case the torque required is not constant. The H.P. at half speed is about $(\frac{1}{2})^3$ or one-eighth of that required at full speed, i.e. $\frac{1}{8} \times 50$ or 6·25 H.P. In order to develop one-eighth of the full-load H.P. at half speed, we need only one-quarter of the full-load torque. The field strength is constant (by hypothesis), hence the armature current must have one-quarter of its full-load value, i.e. $\frac{1}{4} \times 57·5$ or 14·4 A approx. This means that the IR pressure drop in the armature will also have one-quarter of its full-load value, i.e. $\frac{1}{4} \times 11·5$ or 2·875 V.

The speed being halved and the field constant, E_b will be $\frac{1}{2} \times 488·5$ or 244·25 V ;

* No mention is made above of the field current, but this does not affect the conclusion reached. At all speeds the input to the field circuit is 2·5 A at 500 V in the case considered (see § 669), the field being excited at full voltage even when reduced pressure is applied to the armature. At half speed the armature absorbs

$$\frac{250 \times 57·5}{500 \times 60} \text{ or } 0·479 \text{ of the total input to the motor,}$$

while at full speed the armature absorbs

$$\frac{500 \times 57·5}{500 \times 60} \text{ or } 0·958 \text{ of the total input.}$$

In other words, the useful input to the motor at half speed is half the useful input at full speed, but the total input is the same in both cases.

hence the E.M.F. to be applied to the armature is $E = E_b + e = 244.25 + 2.875$ or 247 V approx. The voltage to be absorbed by the resistance in series with the armature is therefore $500 - 247$ or 253 V; and, as the armature current is 14.4 A, the resistance required is $253 / 14.4$ or 17.6 Ω approx.

In this case the power dissipated in the series resistance is 253×14.4 W or only $\frac{253 \times 14.4}{500 \times 57.5} = 0.127$ of the input to the armature at full speed, compared with 0.5 of the input where a constant-torque load is concerned (Case (a)).

In general, the losses involved by the armature resistance method of speed control are less serious the more rapidly the power requirements of the load decrease with falling speed.

As already noted, speed control by resistance in series with the armature is essentially unstable. For instance, if the armature current is doubled by an increase in load, the voltage drop in a fixed series resistance is also doubled, and the speed of the machine will decrease in proportion to the reduced voltage available at the armature terminals. Conversely, on light load the armature current is very small, hence there is little drop of pressure in the series resistance and the machine runs at nearly full speed. An auxiliary 'barring' motor driving through worm reduction gearing is sometimes used to obtain a steady crawling speed.

Combined field and armature-voltage control is often a convenient and economical arrangement where a very wide range of speed variation is desired; field control is then used for the upper, and armature control for the lower part of the speed range.

Diverter Control.—As explained above, the use of resistance in series with the armature of a D.C. shunt-wound motor, in order to obtain low speeds, results in the actual speed of the machine varying greatly with changes in load. The greater the resistance in series, the more marked does the variation in speed become; for example, if the series resistance were so low that the IR drop in it was only 1 V, doubling the load on the machine would increase the IR drop in the series resistance to about 2 V and the P.D. across the armature would be 248 V instead of 249 V, assuming 250 V supply. Obviously this would result in no change of speed of any practical importance. If, however, the IR drop in the series resistance were 200 V when the current was 10 A (see Fig. 330), (a), halving the torque of the load (and therefore the current required by the motor) would reduce the IR drop in the series resistance to 100 V, leaving 150 V across the armature. The field being the same in both cases, the motor speed is about three times as great in the case represented by Fig. 330 (b) as in that corresponding to

Fig. 330 (a).^{*} This wide variation in speed may be reduced by using a *diverter resistance* in parallel with the armature. The current flowing through the diverter contributes nothing to the motor output, but increases the total current consumption. As shown by the following examples, the effect of the diverter is to reduce the variation of speed with load-torque by reducing the variation of the total current through the series resistance. The

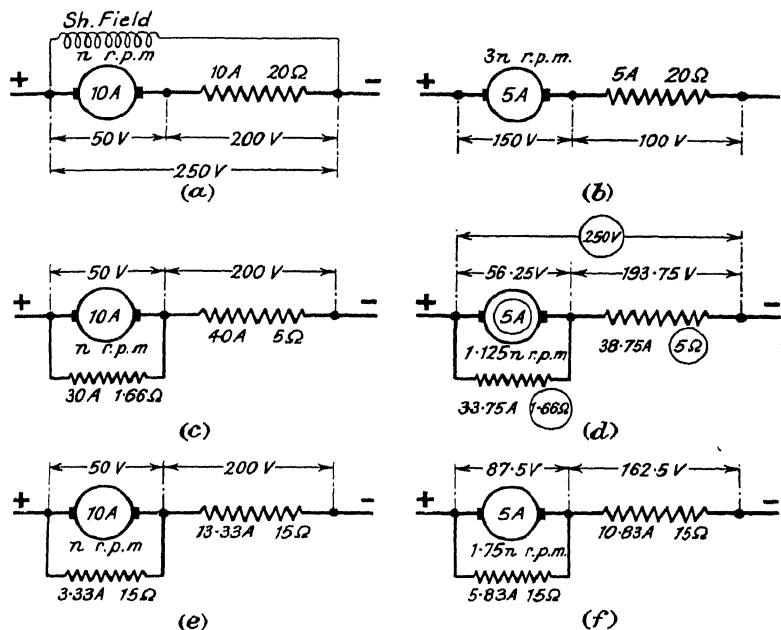


FIG. 330.—Illustrating use of diverter resistance across armature, in conjunction with series resistance, for stabilising speed of D.C. shunt-wound motor. (Note—except at (a) the shunt field winding is omitted for simplicity.)

P.D. applied to the armature is thus stabilised and, with it, the speed of the motor.

Fig. 330 (c) assumes the same load conditions on the motor as those shown in Fig. 330 (a), *viz.* 10 A and a terminal P.D. of 50 V. The equivalent ohmic resistance

^{*} Here and in the following examples it is assumed that the speed is directly proportional to the P.D. across the armature; the error involved by this assumption is negligible so far as the purpose of these examples is concerned. Actually, the back-E.M.F. of the armature is proportional to the speed, and the relation between the applied P.D. E , the back-E.M.F. E_b , the ohmic resistance R of the armature, and the armature current I , is given by $I = (E - E_b) / R$.

of the armature is $50/10 = 5 \Omega$. Suppose that the diverter resistance is one-third of this value, i.e. 1.66Ω , then the current through the diverter is 30 A, the total current is $10 + 30 = 40$ A, and, since the P.D. across the series resistance is 200 V, the ohmic value of this resistance must be $200/40 = 5 \Omega$. It should be noted that, with the same input to the motor itself as in Fig. 330 (a), the total current is now 40 A instead of 10 A, i.e. the power consumption is now four times as great.

Let us now consider what will happen if the load-torque be reduced so that a current of only 5 A is required in the armature circuit. The known values are those entered in circles in Fig. 330 (d), viz.: series resistance, 5Ω ; diverter resistance, 1.66Ω ; armature current, 5 A; supply voltage, 250 V.

Suppose that the speed is x times as high as in the case represented by Fig. 330 (c). Then the P.D. across the armature is approximately $50x$ V; hence the IR drop in the series resistance $= 250 - 50x$ V. But the IR drop in the series resistance also $=$ total amperes $\times 5$ V. Therefore the total amperes $= (250 - 50x)/5$. The armature current is 5 amperes, hence the diverter current $[(250 - 50x)/5] - 5$ amperes. But the diverter current also $= 50x$ V / 1.66Ω . Equating

$$\frac{250 - 50x}{5} - 5 = \frac{50x}{1.66}$$

we find $x = 1.125$.

In other words, the speed in Fig. 330 (d) is $1.125n$ instead of $3n$ as in Fig. 330 (b), n being the speed in the cases shown by Figs. 330 (a) and (c).

Substituting $x = 1.125$ in the above expressions, it is found that the armature P.D. $= 56.25$ V; diverter current $= 38.75$ A; total current $= 38.75$ A (not very different, it will be noted, from the 40 A in Fig. 330 (c)); and the IR drop in the series resistance $= 193.75$ V.

The stabilising effect of the diverter resistance on the motor speed is thus demonstrated, but the price paid is a greatly increased total current consumption. In Fig. 330 (a) the input to the motor is $50/250$ or 20% of the total input; at (b) it is $150/250$ or 60% of the total input; at (c) it is $(50 \times 10)/(250 \times 40)$ or 5% of the total input; and at (d) it is $(56.25 \times 5)/(250 \times 38.75)$ or 2.9% of the total input.

If a diverter resistance of higher value were used, the inefficiency would not be so marked, but, on the other hand, the speed-variation with load would be greater. For example, if the diverter resistance were 15Ω (instead of 1.66Ω as above), the series resistance required for the motor conditions 50 V, 10 A (Fig. 330 (c)) would be 15Ω and the new value of x is 1.75. The conditions are in fact as shown at (e) and (f), corresponding to diagrams (c), (d), but with the new values of diverter and series resistance. The total current is now much less than at (c), (d); and the input to the motor is $(50 \times 10)/(250 \times 13.8)$ or 15% of the total in Fig. 330 (e), and $(87.5 \times 5)/(250 \times 10.3)$ or 10.2% of the total in Fig. 330 (f).

The use of a diverter resistance in parallel with the armature of a shunt motor, in conjunction with series resistance as shown, is thus inefficient in itself but effective in stabilising the speed of the machine on variable load. The actual characteristics of the combination vary according to the values of diverter and series resistance employed, and the reader will find it instructive to work out a series of curves for different conditions.

Speed Variation by Mechanical Control.—If the field and brush system of a D.C. shunt motor be mounted on bearings coaxial with the armature shaft they will run at the full normal speed of the armature but in the *opposite direction*, if the armature be held stationary. If both the field system and the armature be free to rotate each will run at half the normal speed of the armature but in opposite directions. Suppose, for example, that the normal speed of the motor is 1 500 r.p.m. in a clockwise direction, then

- (a) With the field and brushes stationary the armature will run *clockwise* at 1 500 r.p.m.
- (b) With the armature held stationary and the field and brush system free to rotate, the latter will run *anti-clockwise* at 1 500 r.p.m.
- (c) With both the armature and the field and brush system free to rotate, the armature will run *clockwise* at 750 r.p.m., and the field and brush system *anti-clockwise* at 750 r.p.m.

The relative speed between the armature and the field and brush system is 1 500 r.p.m. in all cases and, by means of a differential brake which acts on both members, increasing the braking on the armature as it reduces the braking on the field system, any armature speed from standstill to 1 500 r.p.m. can be obtained.* There are no rheostatic control losses, but there is, of course, the equivalent thereof in the form of frictional dissipation of energy by the brakes. The method offers a convenient means of obtaining zero- to full-speed control in the case of motors of fractional horse-power, *e.g.* motors for sewing machines, watchmakers' lathes, etc. The same principle is sometimes applied to the starting of synchronous motors (§ 722), but in that case the brake on the stator is locked when the motor is up to speed and there is no dissipation of energy at the brake during normal running.

Electrodynamic Braking (§ 715).—The connections of a D.C. shunt-wound motor during normal running and electrodynamic braking are shown diagrammatically in Fig. 331. The field remains almost fully excited by the back-E.M.F. of the armature during the transition stage (*b*), hence a powerful braking torque is

* A full description of a motor developed on this principle and patented by P. T. King is in *The Amateur Mechanic*, Vol. 2, p. 141.

obtained directly the armature is connected to the braking resistance R , Fig. 331 (c), the armature current being now reversed but the field polarity being the same as at (a).

718. Starting and Speed Control of D.C. Series-Wound Motors.—The starting and control of the series-wound D.C. motor

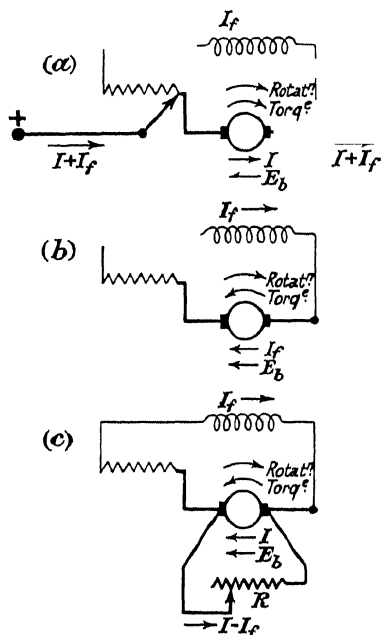


FIG. 331.—D.C. shunt-wound motor. (a) Running; (b) Transition; (c) Electrodynamic braking.

are affected materially by the fact that normally the whole of the armature current flows through the field circuit, the windings being in series. The total resistance of the armature and field windings is not sufficient to prevent an excessive current from flowing when the armature is stationary and therefore developing no back-E.M.F., but the initial rush of current cannot be as heavy as in the shunt motor because the armature is always in series with the field winding and never straight across the mains. Owing to the high inductance of shunt field windings, the field takes a perceptible time to 'build up'; but, from the nature of the case, the field of a series-wound

machine necessarily builds up as rapidly as the armature current, for the same current flows through the armature and the field windings. Series-wound motors up to 5 H.P. or so can generally be switched straight on to the mains unless mechanical considerations require the use of a starting resistance to moderate the acceleration. Small series-wound fan-motors have windings of relatively high resistance and therefore seldom require a starting resistance, particularly as they start 'light,' the load coming on automatically as the fan gains speed.

For larger series motors a starting resistance should always be

employed. The factors distinguishing the design of the starter for a series motor from that of a shunt motor are explained in § 719.

As in all other D.C. motors, the starting torque of the series motor at full field equals the full-load torque when the armature current equals the full-load value. As, however, the field current increases with the armature current, the torque increases more rapidly than the current.* Until the armature begins to rotate, the current is determined by the sum of the resistances of the armature, field winding and starting resistance; and the armature begins to rotate when the current reaches such a value that the torque exceeds the resisting torque of the load.

Again, as in the case of any other D.C. motor, the speed of a series-wound machine can be varied by changing the applied voltage, by changing the excitation of the field, or by a combination of these methods. Whichever method be employed, the speed will still vary automatically as the load changes; that is an inherent property of the series motor.

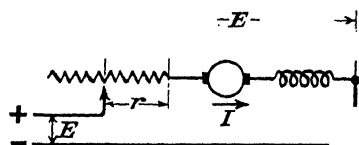


FIG. 332.—Speed control of D.C. series motors by series resistance.

Speed Control by Voltage Variation.—If the motor be supplied from a variable voltage generator, its speed can be varied continuously and without rheostatic loss over the whole range from zero at zero voltage up to normal at full voltage. The torque corresponding to any particular value of current remains the same at all speeds; and the speed is nearly proportional to the applied voltage.

Generally, however, the supply voltage is constant. Continuous speed control by voltage variation can then be obtained by series resistance (Fig. 332), but there is a rheostatic loss, I^2r watts, at all applied voltages V less than E , i.e. so long as there is any series resistance in circuit. As in the case of shunt motors (§ 717), a diverter resistance in parallel with the armature helps to stabilise the speed when running with series resistance. The current flowing through the path in parallel with the armature is added to the armature current in the series field coils and thus prevents racing

* Theoretically, apart from the limitation of the field strength by magnetic saturation, the torque of the D.C. series motor varies with the square of the current (§ 676).

on light load. Indeed, by choosing a suitable value for the resistance shunting the armature the variation in speed from a $\frac{1}{4}$ -load to no-load can be kept relatively small. This method of control is obviously wasteful of energy in both the series and the parallel resistances, but it facilitates stable running at low speeds and loads, *e.g.* when lifting patterns from foundry moulds.

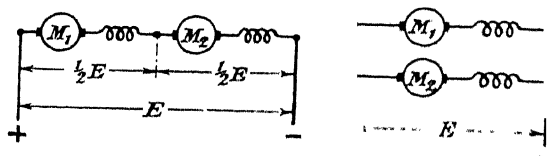


FIG. 333.—Series-parallel control of two D.C. series motors.

Efficient but not continuous speed control by voltage variation can be obtained by series-parallel control (Fig. 333). This method is only applicable to an even number of similar machines driving a single load, *e.g.* a tramcar or a train. Where two motors are used (Fig. 333) the voltage applied to each in the series connection is $\frac{1}{2}E$, and the speed is approximately half that corresponding to

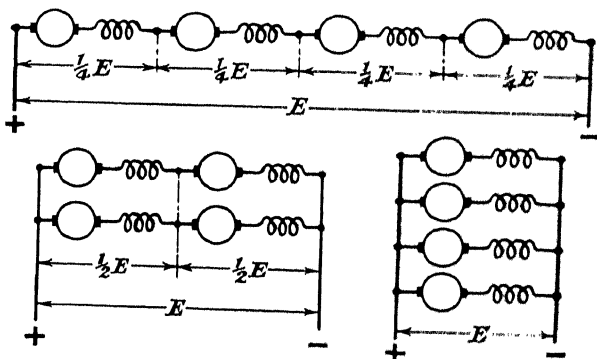


FIG. 334.—Series, series-parallel, and parallel grouping of four D.C. series motors.

operation in parallel on full voltage. If four motors be used (Fig. 334) three combinations are possible, *viz.*: full-series, series-parallel and full-parallel, the corresponding speeds being approximately in the ratio 1 : 2 : 4. As series-parallel control gives at least two efficient running speeds (three, if four motors be used), it is always employed in D.C. traction service. Intermediate speeds

are obtained by series resistance (Fig. 332) which involves rheostatic losses; and sometimes by series-parallel or tap-field control (Figs. 335, 336) which involve no rheostatic loss (*see also* §§ 452, 453, 506, Vol. 2).

Speed Control by Field Variation.—The speed of a series motor cannot be varied efficiently by inserting resistance in series

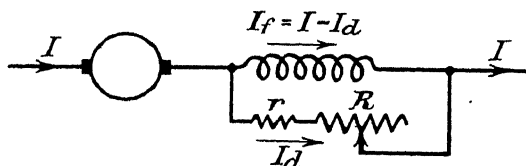


FIG. 335.—Field diverter for speed control of D.C. series motor.

with the field winding (as in the case of the D.C. shunt-wound motor), because such resistance would be also in series with the armature and the conditions would be as shown in Fig. 332. By use of a 'diverter,' however, *i.e.* a variable resistance R , Fig. 335, connected in parallel with the field winding, more or less of the armature current I can be bypassed, leaving only $I - I_d$ to flow

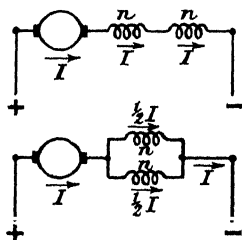


FIG. 336.—Speed control of D.C. series motors by series-parallel field control.

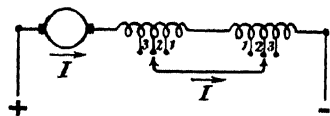


FIG. 337.—Speed control of D.C. series motor by field tapping.

through the field windings; the strength of the field being thus reduced the motor runs at a higher speed the lower the value of R . In order that the field windings may never be completely short-circuited (which would result in the field falling to zero and the machine racing), the diverter circuit contains a suitable permanent resistance r , so that I_f does not fall below a safe value even when R is cut out of circuit. The control of the speed of a shunt motor by field resistance involves very small sacrifice of efficiency because the field current, and therefore the I^2R loss in the regulator, is

small. Now, however, a considerable fraction of the main current is diverted through the resistances r, R (Fig. 335), and the $I^2(r+R)$ loss is correspondingly heavy.

Methods of varying the field excitation for given armature current without rheostatic loss are shown in Figs. 336, 337. In

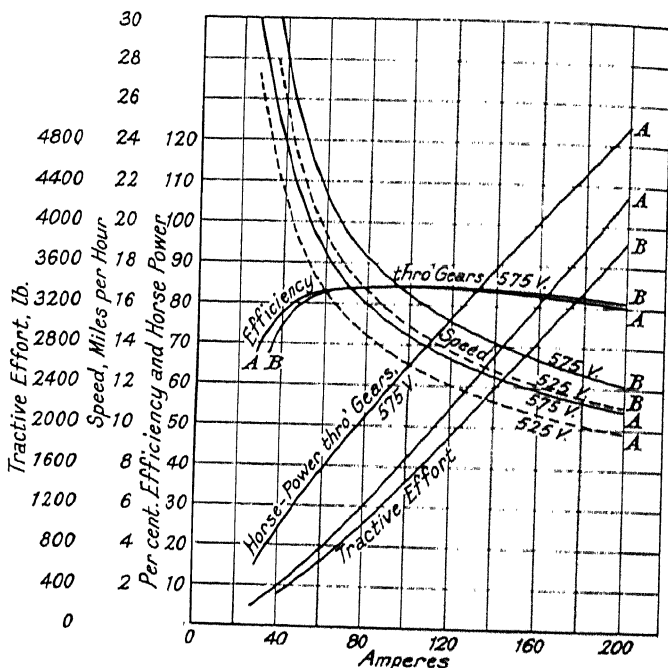


FIG. 338.—Characteristic curves of D.C. series-wound traction motor, showing speed on 575 and 525 V; also, speed control by field diverter. A = full field; B = 25 % field shunted. Gear loss assumed, 5 % at all loads. Ratio, $9\frac{1}{2} : 1$ —36-in. dia. wheels. R.P.M. = M.P.H. $\times 80 \div 2$.

(Courtesy British Thomson Houston Co., Ltd., Rugby.)

Fig. 336 the field winding is shown in two equal sections, each of n turns; and the total ampere-turns of field excitation is $2nI$ when the windings are in series, and nI when the windings are in parallel. The speed of the motor is approximately doubled by changing the field sections from series to parallel connection. In Fig. 337 an equal part of each section of the field winding is short-circuited by the connection between tappings. The full armature current still flows through those parts of the field windings which

are in circuit but the number of effective turns in the field winding is reduced; the reduction in the number of field ampere-turns results in a higher speed of armature rotation.

Fig. 338, relating to a series-wound traction motor, illustrates the effects of variations in the supply voltage, and the different speed-current curves corresponding to full-field and 25 % field shunted respectively.

For such applications as the driving of ships' deck winches, when a higher speed is required at light loads than corresponds to the natural speed-load curve of the series motor, a diverter resistance may be connected in parallel with the series field when light loads have to be handled, thus weakening the field and increasing the speed.

The Scott-Bentley 'discriminator' effects this change automatically. The effects of typical alternative settings of the 'discriminator' are shown in Fig. 339.* In this particular case an output of 240 ton-ft. per min. can be arranged for at any load between 1 and $1\frac{1}{2}$ tons.

If the discriminator brings the diverter into action at $1\frac{1}{2}$ tons load, the speed of hoisting at this and lower loads follows curve A. Alternatively, by using the normal characteristics of the motor (curve C) down to a load of 1 ton, the higher speeds of curve B can be obtained for lighter loads.

The effect is to make the speed-load characteristic of the machine approach the curve D of constant power (*i.e.* speed inversely proportional to weight lifted), thus utilising more nearly the full power of the motor when hoisting light loads.

Electrodynamic Braking (§ 715).—Electrodynamic braking of D.C. series motors may be effected by running them (driven by the load) as self-exciting series generators dissipating their output in a resistance connected across their terminals. If there are two motors, as in a tramcar, they are connected in parallel to the braking resistance, and in this case the track-brake magnet windings may

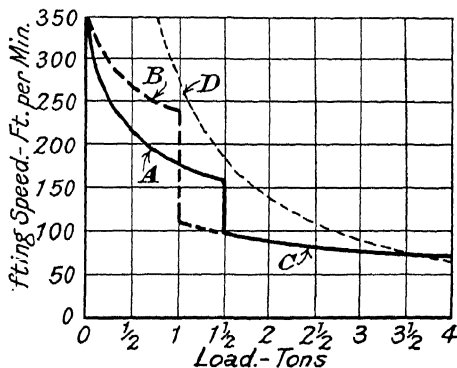


FIG. 339.—Illustrating use of field diverter to increase speed of D.C. series motor at light loads.

* Reproduced by courtesy of Laurence Scott & Electromotors Ltd. (Norwich), the makers of this equipment.

be connected in series with the resistance. In order to ensure equal division of braking load between the two machines an equalising lead may be connected between the common terminals of the armature and field in each, or the armature of each motor may be connected in series with the field of the other. If the output of the motors is to be fed to the supply mains during the braking period, as during the 'regenerative braking' of trains on down gradients, an auxiliary motor-generator set is required for the separate excita-

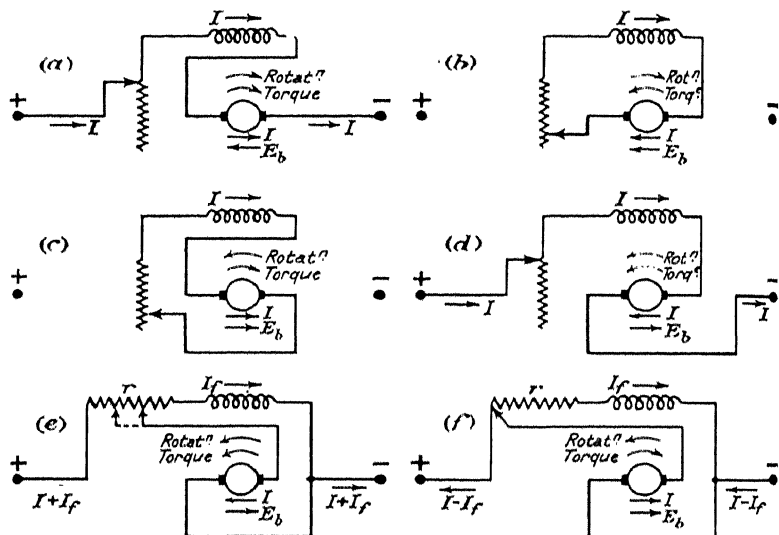


FIG. 340.—D.C. series-wound motor. (a) Forward running. (b) Electrodynamic braking of forward running. (c) Electrodynamic braking of reverse running, e.g. lowering by gravity. (d) Reverse running; lowering by power. (e) Lowering by gravity; separately excited field. (f) Regenerative braking.

tion of the main motor fields, so that a steady voltage somewhat in excess of the supply voltage can be maintained. When the output of the motors is simply dissipated in resistances (rheostatic electric braking), the E.M.F. generated is immaterial. Unless special precautions are taken, electrodynamic braking of series motors does not offer a reliable means of controlling the lowering of crane loads.

Referring to the diagrams in Fig. 340, the connections shown are as follows :—

(a) Normal running; clockwise torque and rotation assumed.

(b) Electrodynamic braking; the armature is still running clockwise but it is desired to utilise its kinetic energy for braking purposes. This demands an anti-

clockwise torque. The armature current, produced by the back-E.M.F. of the armature, is opposite to that in (a), and the field-to-armature connection is reversed so that the field current continues to flow in the same direction as before. The torque is therefore reversed as required.

(c) Motor mechanically-driven reversed by its load (*e.g.* the descending load of a crane), but retarded by electrodynamic braking. The rotation of the armature is now anti-clockwise, hence the back-E.M.F. of the armature is reversed and the current generated flows in the same direction as that supplied at (a). It is desired to develop a clockwise torque in order to retard the motor, which is driven anti-clockwise by the load. The connections must therefore be such that the field current flows in the same direction as at (a).

(d) Motor electrically-driven reversed (*e.g.* where the load of a crane is not heavy enough to descend by itself). Power is taken from the mains; the direction of current in the field windings is the same as at (a), but the flow through the armature is reversed, hence the torque is now anti-clockwise.

On disconnecting the motor from the mains, preparatory to changing from (a) to (b) above, the field current is interrupted, instead of being maintained as in the case of a shunt-wound motor (§ 717). The field therefore falls to the low value corresponding to the remanent magnetism of the iron, the back-E.M.F. of the armature falls correspondingly and, when the connections are made as at (b), there may be appreciable delay in building up the field. The machine may, in fact, fail to excite itself if the residual field is very low or if there is a poor contact in the circuit. To avoid this risk, the field may be separately excited as at (e) and (f), Fig. 340.

(e) Motor separately excited and electrically-driven reversed. Electrically, this corresponds to (d) above, except that there are additional losses in the resistance r . The greater the proportion of r spanned by the brush leads, the higher the P.D. applied to the armature, and the higher the speed of the latter.

(f) Motor separately excited and braked electro-dynamically. With the connections shown at (e), the speed increases as the P.D. applied to the armature is raised. If the load is capable of driving the motor, as when lowering the load of a crane, there may be a certain speed at which the back-E.M.F. of the motor equals the P.D. applied to the brushes. The armature current and therefore the torque developed by the motor will then be zero. If the load drives the motor at a yet higher speed the back-E.M.F. exceeds the applied P.D.; the armature current is reversed, thus developing a retarding torque; and a certain amount of energy is returned to the mains. This is a case of regenerative braking (§ 715).

719. Calculation of Starting Resistances for D.C. Shunt and Series Motors.—The current required to start the motor, or the maximum current increment permitted by the electricity supply authority (whichever is the smaller) determines the total value of the resistance to be placed in series with the armature on the first notch of the starter. This resistance has then to be removed step by step, the amount of resistance removed at each notch being such

that the resultant momentary rush of current does not exceed a predetermined value. The smaller the difference between the maximum and minimum values of current, *i.e.* the finer the subdivision of the total resistance, the more nearly uniform is the acceleration of the machine. Liquid starters have, in effect, infinite subdivision and make possible uniform acceleration provided that the resistance be removed at the correct rate.

The selection of a suitable number of notches for a step-by-step starter and the subdivision of the total resistance between them, to suit the requirements of the motor and load concerned, are primarily matters for the manufacturer of the starter. In order, however, to illustrate the principles involved, the cases of starting resistances for D.C. shunt and series motors are considered briefly below. For a detailed treatment the reader should refer to specialised text-books or papers.*

Starting Resistance for D.C. Shunt Motor.—In Fig. 341, R the resistance of the armature of the shunt motor; R_s the total starting resistance; and $r_1, r_2, r_3 \dots r_n$ the successive divisions of R_s . It is assumed that the field is kept constant at its maximum value throughout the starting period; and that the current limits are I_{\max} and I_{\min} . If I_{\max} flows on the first step with the motor at standstill (back-E.M.F. zero), $R_1 = V / I_{\max}$ and $R_s (= R_1 - R) = (V / I_{\max}) - R$. (The total resistance R_s thus determined may have to be increased in order to obtain an initial current within the limit prescribed by the supply authority).

When the current has fallen to I_{\min} on step *A* we have: $V = R_1 + I_{\min} R_1$, where R_1 = back-E.M.F. of the motor. On advancing to step *B* the back-E.M.F. remains constant (the field being constant) until the motor begins to accelerate, but the current increases to I_{\max} . At the moment of making contact with *B* we have, therefore: $V = R_1 + I_{\max} R_2$. Hence $R_1 + I_{\min} R_1 = R_1 + I_{\max} R_2$; whence $R_2 / R_1 = I_{\min} / I_{\max} =$ say η . Similarly, when we advance to step *C*, we have $R_3 / R_2 = \eta$; and, finally, $R_n / R_{n-1} = \eta$. Therefore,

$$R = \eta R_n = \eta^2 R_{n-1} = \dots = \eta^n R_1 = \eta^n V / I_{\max};$$

from which $\eta = \sqrt[n]{(R I_{\max} / V)}$.

Knowing the number of steps n in the resistance, the armature resistance R , the maximum current I_{\max} , and the supply voltage V , we can calculate η , the ratio between successive values of total resistance R_1, R_2 , etc., using the above formula.

The individual steps r_1, r_2 , etc., are then calculated as follows:—

$$\begin{aligned} r_1 &= R_1 - R_2 = R_1(1 - \eta), \\ r_2 &= R_2 - R_3 = R_2(1 - \eta) = \eta R_1, \\ r_3 &= \eta^2 R_1, \\ r_4 &= \eta^3 R_1, \\ &\dots \dots \dots \\ r_n &= \eta^{n-1} R_1 \end{aligned}$$

* See, for example, 'The Analytical Determination of the Steps in the Starter of a Series Motor,' S. Parker Smith, *Jour. I.E.E.*, Vol. 58, p. 645 (this method is summarised here); and 'A Universal Chart Method of Calculating Starting Rheostats for D.C. Motors,' A. T. Dover, *ibid.*, Vol. 60, p. 867.

and, as a check, $r_1 + r_2 + r_3 + \dots + r_n$ should equal R_s . It will be seen that r_1, r_2, r_3 , etc., form a geometrical series of ratio p .

Starting Resistance for D.C. Series Motor.—Referring again to Fig. 341, the value R must now include the resistance of the *series field winding as well as that of the armature*. As before, $R_1 = V / I_{\max}$ and $R_s = (V / I_{\max}) - R$. The distinction now is that on moving from step A , at the moment when the current is I_{\min} and the field flux has fallen to Φ_2 , the current increases to I_{\max} directly step B is reached, and the field flux simultaneously increases to Φ_1 , hence the back-E.M.F. rises in the ratio Φ_1 / Φ_2 before the motor accelerates further. We have no longer a constant field, and therefore no longer the same value of back-E.M.F. immediately before and after advancing one step. The flux ratio $f = \Phi_1 / \Phi_2$, corresponding to the current ratio $c = I_{\max} / I_{\min}$, can be determined from the magnetisation curve of the motor, *i.e.* the curve showing the field flux plotted against values of current.

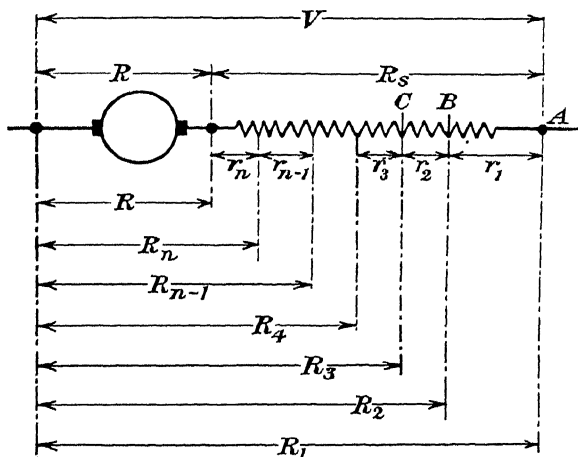


FIG. 341.—Illustrating calculation of steps for starting resistances of D.C. shunt and series motors.

NOTE: R = resistance of armature alone in shunt motor;
but R = resistance of armature *plus* series field in series motor.

The back-E.M.F., E , of the motor is proportional to the product of field flux Φ by the armature speed N r.p.m.; also, $E = V - RI$, where V = applied voltage, I = current in amperes, and R = ohmic resistance of motor plus series resistance. Hence

$$N = a \cdot E / \Phi = a(V - RI) / \Phi,$$

where a is a constant for the motor concerned.

At the moment of leaving step A ,

$$E' = V - R_1 I_{\min} = N \Phi_1 / a.$$

At the moment of reaching step B , the speed being still N ,

$$E'' = V - R_2 I_{\max} = N \Phi_1 / a.$$

Hence
$$\frac{R_1''}{R_1'} = \frac{V - R_2 I_{\max}}{V - R_1 I_{\min}} = \frac{\Phi_1}{\Phi_2} \cdot f,$$

therefore
$$R_2 = k R_1 = \frac{V}{I_{\max}} \cdot (f - 1), \text{ where } k = f / c.$$

Thus
$$r_1 (= R_1 - R_2) = R_1(1 - k) + \frac{V}{I_{\max}} (f - 1).$$

But
$$R_1 = V / I_{\max}, \text{ therefore } r_1 = R_1(f - k) \quad (1)$$

and
$$r_2 = k r_1,$$

$$r_3 = k r_2,$$

and so on.

If there are n steps in the starter, the condition to be fulfilled is

$$\frac{V}{I_n} (f - 1) \frac{1 - k^n}{1 - k} + R = R_1 k^n = 0 \quad (2)$$

(see S. Parker Smith, *ibid.*, for proof).

The factors which must be known are: The supply voltage V ; the magnetisation curve of the motor; the number of steps n ; the motor resistance R (armature plus field); and either I_{\max} or I_{\min} but not both. If I_{\max} be known, three likely values of I_{\min} are assumed; the corresponding values of c (I_{\max} / I_{\min}) are calculated; the corresponding values of f ($= \Phi_1 / \Phi_2$) are found from the magnetisation curve; the values of k ($= f / c$) are calculated; the value of R_1 ($= V / I_{\max}$) is calculated; and the values of the expression at (2) above are determined. These values are plotted against the assumed values of I_{\min} and from the curve obtained it is at once apparent what value of I_{\min} will satisfy eqn. (2). Recalculating f and k for the correct value of I_{\min} , we can then solve eqn. (1) for r_1 , and thence determine $r_2 = k r_1$; $r_3 = k r_2$; and so on. As before, the starter steps are in geometrical progression, but the ratio is now $k = f / c = I_{\min} \Phi_1 / I_{\max} \Phi_2$. As a check, the sum of the calculated values for r_1, r_2, r_3 , etc., should equal R_s .

For the application of the above method to the determination of the resistance steps for two series motors with series-parallel control, see S. Parker Smith, *loc. cit.*

720. Starting and Control of D.C. Compound-Wound Motors.—Small D.C. motors with heavy compounding (*i.e.* a high proportion of series field excitation) can be switched straight on to the supply, the series field winding ensuring immediate availability of a considerable starting torque and a speedy reduction of current by the development of back-E.M.F. (see also § 718). Generally, however, a compound motor with 10 to 30 % of series excitation (cumulative), as used for general industrial purposes is started and controlled in the same way as a shunt motor. Fig. 342 shows diagrammatically the use of a starter R , and a shunt regulator F for speed regulation. If the shunt field be much reduced, by the insertion of resistance at F , the effective ratio of the compounding is increased, *i.e.* the proportion of series ampere-turns increases and the characteristics of the machine resemble more closely those of a series motor. In other words, the decrease in speed with increas-

ing load becomes more pronounced as the shunt field is weakened to increase the speed. The increase in speed effected by a given percentage reduction in the shunt field is, of course, less in a cumulative compound motor than in a plain shunt-wound machine, because the series field of the compound motor remains the same for the same armature current.

A difficulty in the way of compounding a motor which is arranged for wide speed variation by means of a shunt regulator is that the field cores are necessarily nearly saturated by the maximum shunt field, in order that a suitable field may still be maintained at the other end of the speed range (minimum shunt field). The compounding effect of the series turns is very small when the field system is near magnetic saturation; but very large, both actually and relatively, when the shunt field is weak and the pole cores far

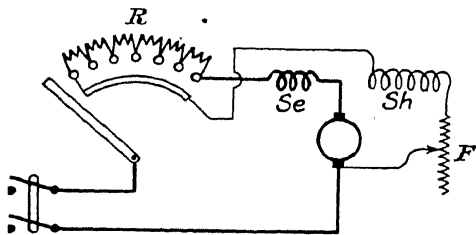


FIG. 342.—D.C. compound-wound motor with starter and shunt regulator.

from saturation. Unless the degree of compounding and the range of shunt regulation are both moderate, the load-speed characteristics of the motor will resemble those of a shunt motor at low speeds (full shunt field), and those of a series motor at high speeds (weak shunt field); such a combination is generally neither desirable nor safe. The difficulty may be overcome in certain cases by providing special means for varying the series excitation to suit the shunt excitation in use at any particular moment (*see Indirectly Compounded Motors*, § 677).

If the series turns of a compound motor are short-circuited after the motor has been started, the machine is then a plain shunt-wound motor and its speed can be varied by a shunt-regulator in the ordinary way.

721. Control of A.C. Motors: General.—The synchronous A.C. motor is inherently a constant speed machine, its speed in

r.p.m. being numerically equal to $60 f / p$: where f = supply frequency in cycles/sec., and p = number of *pairs* of poles. For example, the speed of a six-pole synchronous motor on 50-cycle supply is $60 \times 50 / 3 = 1\,000$ r.p.m. Three methods of speed variation are available: (1) The frequency, f , can be varied by altering the speed of the alternator or by feeding the motor from a constant-frequency supply through a cascade set, providing variable frequency at the motor. The first method of frequency-variation necessitates the use of a separate alternator for the motor or group of motors concerned, and is therefore only applicable to such cases as the electrical propulsion of ships, and certain industrial establishments generating their own current for a number of motors requiring the same speed variation. Frequency variation by means of a cascade set has been used to provide two different speeds for a passenger lift, one for the main travel and a lower speed in preparation for stopping. (2) The number of poles, $2p$, can be varied by using a special winding, with means for changing the connections so as to change the number of poles produced. The simplest arrangement provides a certain number of poles or a number twice as great, corresponding to two speeds in the ratio 2:1. (3) The stator can be driven mechanically at different speeds N r.p.m. so that, although the speed of the rotor with regard to the stator remains constant at n r.p.m., the actual speed of the rotor is $n \pm N$ r.p.m., N being added to n if the stator is driven in the same direction as the rotor, and subtracted if it is driven in the opposite direction.

At no-load the induction motor runs practically at synchronous speed (calculated as above), but as the load increases the speed decreases owing to the increasing amount of the rotor 'slip.' The three methods of speed variation mentioned for synchronous motors are applicable to induction machines and, in addition, speed control can be obtained by increasing the 'slip.' At full-load the slip may normally be 2% in large motors and 5 to 10% in small machines, but it can be increased by inserting additional resistance in the rotor circuit or by using an auxiliary machine to vary the slip without the waste of energy resulting from rheostatic control.

The speed of the simple series A.C. motor can be varied by regulating the voltage applied to the machine, using a variable-tapping transformer or an induction regulator for the purpose. In the many special types of A.C. commutator motors, with different systems of supplying energy to both the stator and the

rotor, speed control is obtained by altering the conditions in the rotor, *e.g.* by brush-shifting or by varying the E.M.F. applied to fixed brushes.

These general notes are elaborated in §§ 722-735.

722. Starting and Control of Synchronous A.C. Motors.—

The synchronous motor being essentially an alternator reversed in function, it may be started by running it up to (or just above) synchronous speed by means of an auxiliary pony motor (see § 410, Vol. 2) and then synchronising it like an alternator. For industrial power service, however, it is much more convenient to use a self-starting, self-synchronising machine. A synchronous motor will start and run as a hysteresis motor, *i.e.* with the rotor not excited except by induction from the stator, but the torque and P.F. are then very low.

With a squirrel-cage or phase-wound starting winding in the pole-shoes of the D.C. field system (usually the rotor, see § 679), a salient-pole synchronous motor can be started like a squirrel-cage or slip-ring induction motor, as the case may be (§ 724); different starting characteristics can be obtained according to the design of the starting winding, particularly as regards the effective resistance of the latter. A high-resistance squirrel-cage winding in an induction motor gives increased starting torque (as compared with a low-resistance winding), but it also involves increased loss in the rotor copper during the whole time the motor is in service. In the synchronous motor, however, the high-resistance squirrel-cage results in increased starting torque without affecting the normal efficiency of the motor, because there is no current in the starting winding when the motor is running synchronously. The resistance of the starting winding must not be made too high or the pull-in torque will be inadequate.

When starting a high-speed synchronous motor as an induction motor (by means of an auxiliary winding in the pole shoes), the voltage applied to the stator must be reduced to keep the initial current within acceptable limits. Thus the initial kVA consumption may be 6 or 7 times the normal full-load value if a 1 000 to 1 500 r.p.m. synchronous motor be connected to the full line-voltage; and in order to keep the initial current down to 2 to $2\frac{1}{2}$ times full-load value, it would be necessary to reduce the applied voltage to, say, 60 % of normal. On the other hand, a slow-speed motor (100 to 200 r.p.m.) can be connected straight

to the mains and the initial current will not exceed 2 to 3 times full-load value.

Reduced voltage at the stator terminals may be obtained by using series resistance or reactance or, preferably, by means of an auto-transformer or star-delta switching. When a *squirrel-cage* starting winding is employed from 30 to 40 % of full-load torque can be obtained at starting, with about $1\frac{1}{2}$ times the full-load current. When the motor has thus been brought up to 95 to 98 % of its synchronous speed the D.C. excitation is applied to the rotor field system and the latter pulls into synchronism with the rotating field of the stator, provided that the resisting torque of the load does not exceed, say, 1 to $1\frac{1}{4}$ times full-load torque. If the salient-pole synchronous motor be provided with a 3-phase winding (instead of a squirrel-cage winding) in the pole shoes of the D.C. field system, the machine is started like a slip-ring induction motor (§ 724), and when 95 to 98 % of the synchronous speed has been reached the 3-phase starting winding is short-circuited (thereafter acting simply as a damping winding), and D.C. excitation is applied to the field coils. With this arrangement a starting torque equal to about $1\frac{1}{2}$ times full-load torque can be obtained; the pull-in torque is from 1 to $1\frac{1}{4}$ times full-load torque; and, if pulled out of step by overload, the motor can run for 5 or 10 minutes asynchronously without serious overheating. A synchronous-asynchronous motor (§ 731) can run indefinitely as an induction motor within the limits of its rating.

It is often arranged that modern synchronous motors start automatically under the control of a press button, float contact, or other master switch. The time required to reach full 'induction' speed (about 95 % of synchronism) varies with the load. The automatic closing of the D.C. excitation switch can, however, be made to occur at the correct moment by means of a frequency-relay actuated when the frequency of the slip-E.M.F. induced in the field coils falls to a predetermined value.

During the starting period a high voltage is induced in the D.C. field coils (2 000 V or so may appear at the slip rings). Using a low-voltage exciter (say 125 V) enables the number of turns, and hence the E.M.F. induced in the field coils, to be kept down. The exciter is mounted on the extended shaft of high-speed motors, or chain-driven in the case of low-speed motors; its voltage should not be higher than required by the P.F. desired in the motor,

otherwise there is needless waste in the field rheostat. A sectionalising switch is often used to subdivide the D.C. field circuit of the motor and thus prevent the induction of dangerous voltages during starting. Alternatively, the field circuit may be short-circuited through a field discharge resistance during the starting period. Starting with the field circuit 'open' results in maximum initial starting torque, but a greater pull-in torque is obtained when the field is short-circuited through a resistance, the best value of which may be found by trial.

Two-pole synchronous motors (§ 679) are built only in large sizes, say 1 000 H.P. and over, and are necessarily high-speed

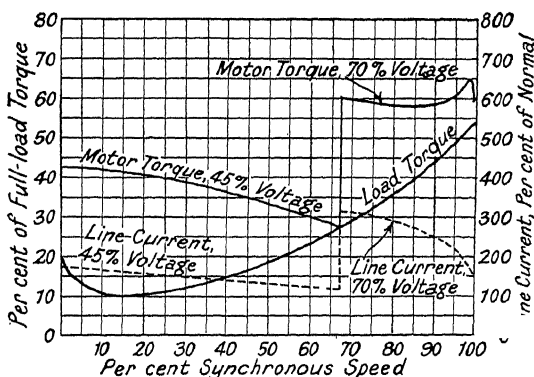


FIG. 343.—Characteristics of two-pole synchronous motor started by two-step compensator.

machines (3 000 r.p.m. on 50-cycle supply). They are started as squirrel-cage induction motors, a special winding being provided on the rotor for that purpose. The machine itself would stand the mechanical shock of being started on full voltage, but, in order to avoid the very heavy current rush which would then occur (say, 10 or 11 times the full-load current, see § 340, Vol. 1), it is advisable to employ a two-step compensator starter, giving reduced voltages of, say, 45 and 70 % of full line voltage. Alternatively, external reactance may be connected in series with the motor to reduce the current rush during the starting period. Figs. 343 and 344 * show torque and current curves for a 1 500 H.P., 3 600 r.p.m.,

* From 'Two Pole Synchronous Motors,' by D. W. McLenegan and I. H. Summers, *Jour. Amer. I.E.E.*, Vol. 47, p. 585.

60-cycle, two-pole synchronous motor started at reduced voltage by a two-step compensator (Fig. 343), and at full-voltage with two

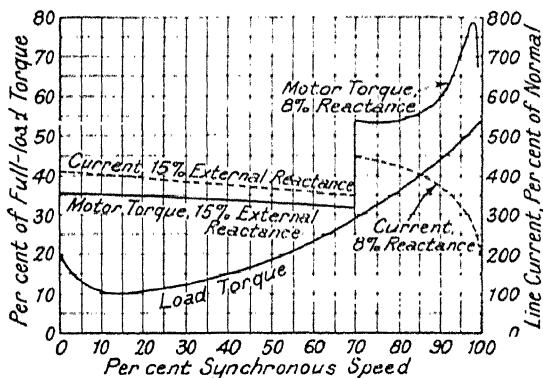


FIG. 344.— Characteristics of two-pole synchronous motor started by two-step series reactor.

values of external reactance (Fig. 344). The load torque curve in both cases is that of a centrifugal compressor with the discharge gate closed. Though the series reactance is the simpler and cheaper method of starting, the current rush is considerably heavier than where a compensator is used. The starting connections used in the latter case are shown in Fig. 345, the sequence of operations being as follows:—

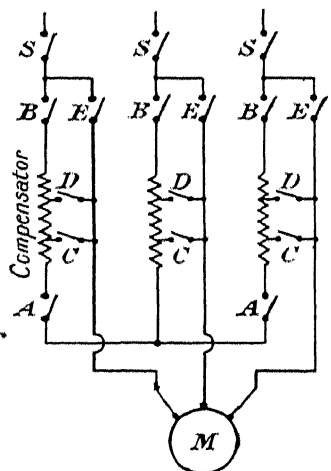


FIG. 345.— Two-step compensator for starting two-pole synchronous motor, with Korndorfer connection for transfer to full voltage.

The neutral point of the auto-transformer is closed by switches *A*. The main circuit breaker *S* and the compensator breaker *B* being closed, the low-voltage tapping is completed by switches *C*, thus applying 40 to 45 % of normal voltage to the motor *M*. After reaching about 70 % of normal speed, the voltage applied to the motor is increased to 70 % of normal voltage by opening the breaker *C* and closing *D*. The reactance of the auto-transformer reduces the current rush which would otherwise result from this increase in voltage. If the load is not too great (see Fig. 343) the motor can be synchronised at 70 % of normal voltage by switching on

the D.C. excitation. The Korndorfer connection (Fig. 345) enables the transfer

to full voltage to be made without interrupting the power supply. The neutral breaker *A* is opened first; this leaves the motor connected to the line through the upper sections of the compensator as series reactors, and the voltage at the motor terminals is about the same as when the switches *A* were closed, or even a little lower. The running circuit-breaker *E* is then closed, short-circuiting the series reactance (i.e. the upper part of the compensator) and applying full-voltage to the motor. Finally, the compensator breaker *B* is opened.

With this method of starting, the maximum current taken from the line is limited to about three times the normal full-load value (see Fig. 343).

If either the motor torque or the initial current of a synchronous motor is excessive when starting at full voltage, the voltage applied to the motor at starting may be reduced by an auto-transformer or by a series reactor. The latter requires simpler switchgear, and smoother starting is obtained, the torque approaching the full-voltage value as the speed increases. The advantages of reactor starting can be obtained without an external reactor by using multiple windings in the primary (usually the stator) of the synchronous motor, so arranged that part of the winding is used during starting and the whole for normal operation. The following particulars * explain the method and the characteristics which it produces:—

A double primary winding is generally employed, the coils of one 3-phase winding being laid in slots 1, 3, 5, 7, etc., while those of the other winding are placed in slots 2, 4, 6, 8, etc. One of the two windings is permanently in star connection. The star points of the phase coils in the other winding are led out to a 2-pole circuit breaker which is open during starting and closed when the motor reaches 90 % or more of synchronous speed. The outer ends of corresponding phases in the two windings are in parallel. Current thus flows through only half the total number of stator coils during starting, and through both windings in parallel when the motor is up to speed. The effect of this arrangement is to increase the reactance and reduce the torque and kVA inrush during starting. The motor is synchronised after closing the star connection of the second winding, or, if the load is light, before the second winding is brought into use.

Fig. 346 relates to a 3 000-H.P., 125-r.p.m., 3-phase, 25-cycle, 6 600 V motor, and shows the torque-speed and current-speed curves for the machine as started with both windings and with only one winding in use (full voltage in both cases). The use of only one part of the multiple winding reduces the starting torque to about half and the starting current to about two-thirds the value corresponding to full-voltage starting with both windings in use. These ratios, being fixed by the relative magnetisations produced by one and two windings, are not capable of adjustment, but as the motor comes up to speed on the single winding, the torque approaches the

* From 'Multiple Winding Starting Method for Synchronous Motors,' by D. W. McLeneghan and A. G. Ferriss, *Gen. Eng. Rev.*, Vol. 33, No. 5, and *Power Engineer*, Vol. 26, p. 114.

normal full-voltage torque curve (as in reactor starting), and there is only a small change in torque when the second winding is energised at 90 to 95 % of synchronous speed. There is no interruption of power supply once starting has been commenced, and the motor efficiency suffers little, if at all, from the use of two windings. Normal pull-in torque can be obtained by closing the second winding before synchronising.

The new method of starting is applicable to any load which could be started by the same motor using both windings and a 70 % auto-transformer tapping. It is well suited to such loads as fans and pumps in which the load increases with the speed, and it is also recommended for loads embodying gears or belts; even if the motor will not start with the single winding it 'takes up the slack,' and when the second winding is closed the set starts without severe mechanical shock.

Multiple winding starting can also be applied to polyphase induction motors, provided that the design of the machine does not

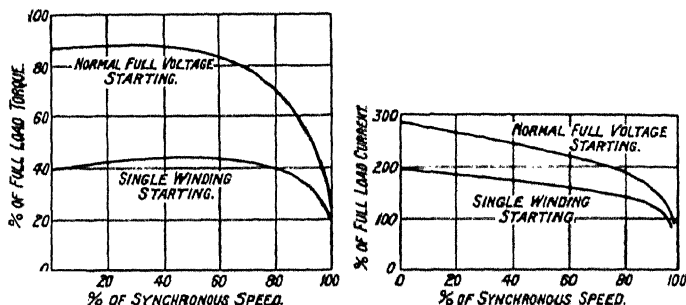


FIG. 846.—Torque-speed and current-speed curves for double-wound synchronous motor during starting period.

permit the development of appreciable harmonic torques when only the alternate coils are energised.

Starting by Clutch or Free Stator.—Where higher starting-torque is demanded by the load than can be obtained by starting a synchronous motor as an induction motor, a clutch may be used so that the motor can be synchronised on no-load and then be engaged smoothly with its load. Once the motor has been synchronised it can apply any torque up to its pull-out torque (say 1½ to 2 times full-load torque) to start the load.

A magnetic clutch may be used between the motor and the load, or the rotor may be direct coupled to the load and the stator may be mounted in bearings so that it can rotate freely during the starting period, the rotor being meanwhile held stationary by the resistance of the load. When the stator has reached synchronous speed and pulled into step on no-load (with a current consumption equal to about half the full-load current), a hand break is applied

to the stator and the latter is gradually brought to rest while the rotor and its load are accelerated to full speed. The rotor begins to turn directly the breaking torque applied to the stator exceeds the resisting torque of the load on the motor shaft, and the relative speed between the stator and rotor remains equal to the synchronous speed of the machine during the whole time the load is being accelerated. If the torque between the stator and rotor exceeds the pull-out torque, the motor falls out of step and a fresh start must be made. If the stator band brake be applied by a weighted lever, which is released by a trunnion block driven by a servomotor, the main motor can be started and stopped by a press button.

Motors of this type are applicable with advantage to any constant-speed load demanding a high starting torque, owing to high inertia, initial frictional resistance, etc. Such loads include heavy lineshafts; pulp beaters; crushing, grinding, or pulverising machinery left full of material; large air blowers; compressors and pumps without unloading valves or by-passes; vacuum pumps; and so on. Although this method of starting has been used successfully in various high-power drives, it involves the complication of special bearings for the stator; and slip rings with brushes to maintain connection between the supply (possibly at 6 600 V or higher pressure) and the stator windings. Also, it is impossible with this system to use a direct-coupled exciter for the D.C. field.

Speed Variation of Synchronous Motors.—As ordinarily used, the synchronous motor is a machine of definitely constant speed, but its speed can be changed by varying the frequency of the supply (this is usually impracticable), or by varying the number of poles by re-connecting the windings. For example, the speed can be halved by doubling the number of poles in both the stator and the rotor. A certain 2-phase, 2 300 V motor built on this principle by the G.E.C., Schenectady, has the ratings and performances summarised in Table 131.

The D.C. field poles are arranged in pairs which are of opposite polarity for low-speed operation, but of like polarity (thus halving the effective number of poles) for high-speed operation. The requisite change in connections is made by a switch which reverses the connections of alternate polar windings. A corresponding change is made simultaneously in the stator phase connections.

Typical applications of this class of motor are to driving an

alternator at two different speeds, for different frequencies; driving a colliery fan at half-speed until full-speed is required; driving an electrically-propelled ship at half-speed, without changing the speed and frequency of the supply alternator; and, in general, driving any load where a 2:1 speed ratio is required, particularly at constant torque, *i.e.* with the H.P. proportional to the speed.

Dynamic Braking of Synchronous Motors.—Synchronous motors can be braked dynamically by disconnecting the stator winding from the supply circuit and short-circuiting it through a resistance. The D.C. field excitation being fully maintained, the motor now runs as an alternator, and the kinetic energy of the rotor and

TABLE 131.—*Rating and Performance of Pole-Changing Synchronous Motor.*

	12-pole Connection.	24-pole Connection.
R.P.M. on 60-cycle supply	600	300
Rated H.P.	5 000	2 500
Starting torque (times full-load)	2·2	1·1
Starting current (times full-load)	7·7	3·7
Efficiency, per cent., at full load	95½	95½
" " ½-load	95	95½
" " ¼-load	93½	94½
" " ⅓-load	89	91½

the driven load is rapidly dissipated as heat in the resistances connected across the stator terminals. According to K. B. Spear,* a synchronous motor can be stopped by this method within a number of revolutions equal to from 1 to 2 % of the normal r.p.m. according to the inertia of the rotating parts and the characteristics of the machine. In other words, a 400 r.p.m. motor can be brought to rest in from 4 to 8 revolutions and, as its average speed during the period of retardation is $\frac{1}{2} \times 400$ or 200 r.p.m., the time occupied in stopping the motor will be from 1·2 to 2·4 seconds. Dynamic braking stops a synchronous motor more rapidly than 'plugging' the machine by reversing the applied current†; and it has the

* *Power*, Vol. 67, p. 856.

† Accurate and practical formulæ for determining the number of revolutions and the time required to stop a synchronous machine by dynamic braking are given by C. E. Kilbourne and I. A. Terry, *Electrical Engineering (Jour. Amer. I.E.E.)*, Vol. 51, p. 843. These authors give the following comparisons between plugging and

further advantage that it is independent of the power supply and can therefore be applied even if the main supply has failed. The D.C. field, however, must be maintained during the braking period. Provision should be made for the dynamic braking of synchronous motors driving saw mills, steel mills, rubber mills or any other machinery which may have to be stopped quickly in order to safeguard workmen or for any other reason. The control circuits can be so arranged that, on pressing any one of a number of emergency stop buttons located wherever desired, the motor is stopped by dynamic braking whether it is in process of being started, stopped or running normally.

The equipment of an automatic starting panel with provision for dynamic braking (Spear, *loc. cit.*) would include starting and running contactors, field relay and contactor, dynamic braking contactor, auto-transformer, dynamic braking resistor, timing relays, and A.C. and D.C. ammeters.

D.C. excitation must be present before the machine can be started and failure of excitation at any time shuts down the motor.

Starting.—Pressing the start button energises the accelerating contactor, connecting the auto-transformer to the line and the motor to the transformer tappings. After an interval determined by the timing relay the accelerating contactor opens and the line contactor closes; the motor is thus connected directly to the line. When the machine reaches about 95 % of synchronous speed, a relay closes the field contactor and the motor pulls into step.

Normal Stop.—Pressing the stop button causes all the control circuits to be de-energised and, as the field contactor opens, the field is short-circuited through the field-discharge resistor.

Emergency Stop.—Pressing any one of the emergency stop buttons de-energises the control relay. This causes the line contactor to open and the field contactor to remain closed. Simultaneously, the spring-set dynamic braking contactors are closed and the motor comes to rest within a second or so. A timing relay opens the field contactor after a predetermined interval; the D.C. excitation is thus removed after the machine has been stopped by dynamic braking.

Resetting.—Before the motor can be restarted, after an emergency stop or after failure of excitation, a reset button must be pressed. This energises the control

dynamic braking in stopping an average 1 000 H.P., unity-P.F., mill-type synchronous motor :—

Motor Speed R. P. M.	Plugging.		Electrodynamic Braking.	
	Revs. to Stop.	Secs. to Stop.	Revs. to Stop.	Secs. to Stop.
1 200	15.60	1.72	9.00	0.98
600	5.50	1.21	4.32	0.95
300	2.90	1.28	2.40	1.05
150	1.65	1.45	1.41	1.24
72	1.02	1.87	0.85	1.56

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relay, connects the control circuit to the starting button, and opens the dynamic-braking contactors, thus disconnecting the braking resistance from the stator. The machine can then be started as above.

Reversal of a 3-phase synchronous motor is effected by interchanging two of the supply leads, so as to reverse the direction of rotation of the A.C. field.

723. Control of Polyphase Induction Motors.—The notes in §§ 724, 725 relating to the starting and speed control of ordinary squirrel-cage and wound-rotor polyphase induction motors should be read in conjunction with §§ 681 to 683; and reference should be made to §§ 684 to 688 for information concerning special types of polyphase induction motors. Cascade and variable-speed sets are dealt with in §§ 694, 727-729.

Certain of the methods of starting and speed control are equally applicable to squirrel-cage and slip-ring induction motors, and, when considering the effects of various systems of control, it should be remembered that squirrel-cage motors of appropriate design have characteristics comparable with those of slip-ring machines (§ 681).

Representative switchgear used for the control of induction motors is described in § 738.

724. Starting Polyphase Induction Motors. The inherent starting characteristics of squirrel-cage and slip-ring motors are explained in §§ 681 to 683, and compared in Table 121, § 684. Supplementary information is given below concerning:—

- (a) Starting at full voltage, by switching straight on to the supply.
- (b) Starting at reduced voltage, obtained by resistance or reactance in series with the supply leads; by star-delta (3-phase) or series-parallel (2-phase) switching; or by auto-transformer.
- (c) Starting by additional resistance in the secondary circuit (applicable only to wound-rotor or equivalent machines).

The case of special squirrel-cage machines, in which the effective resistance of the rotor winding is altered by current-displacement or similar means, is considered in §§ 684, 685.

(a) *Starting at Full Voltage.*—Though the rules of the supply authority must, of course, be observed, there can hardly be any rational objection on technical grounds to the full-voltage starting of any squirrel-cage induction motor up to 10 or 20 H.P. on a modern industrial supply network. High-reactance squirrel-cage

induction motors, designed specially for starting on full voltage, usually take from 4 to 5 times the full-load current at the moment of starting. Machines of this type up to 20 or 30 H.P. can generally be used in combined lighting and power circuits without causing trouble from lamp flicker on starting. Indeed, under favourable conditions of motor location with regard to the transformer and large secondary cables motors of 100 or even 200 H.P. (at low speed ratings) can be started at full voltage in combined lighting and power networks.*

In American steel works high-reactance squirrel-cage motors of such ratings as 150 H.P., 750 r.p.m., 220 V, driving excitation motor-generator sets, are regularly started by switching straight on to the line.

The effect of the sudden mechanical shock on the driven load must be considered where full-voltage starting is employed; and the stator end-windings of the motor need special bracing, particularly in high-power, high-speed machines, the initial current being relatively heavier and the length of the end connections greater than in low-speed machines.

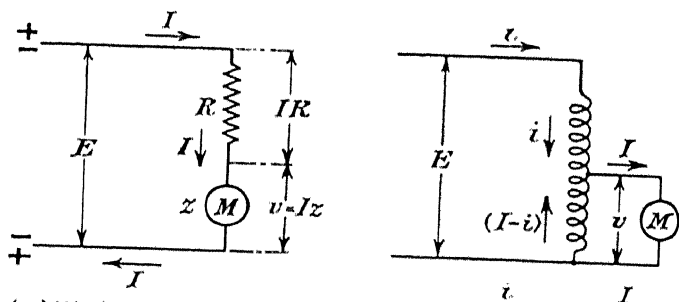
Where only a few motors are employed, full-voltage starting may increase the maximum demand of the installation very considerably, but this should not be a serious consideration where many motors are used; *see also* § 682.

In view of the fact that the initial current is from 4 to 7 times the full-load value when starting at full voltage, special provision must be made to protect the motor against overload. One solution is to use a double-throw knife switch connecting the motor through fuses of normal rating when in the running position, but provided with specially heavy fuses (or no fuses) on the starting side. It is obviously undesirable to start the motor with no local fuses in circuit, and even if specially heavy fuses be used on the starting side, a spring or other device must be used to prevent the switch being left in this position. The use of additional fuses in parallel with the running fuses during starting is a better solution, the supplementary fuses being cut out of circuit automatically as the switch goes to the running position. A manual or automatic switch with a thermal overload release, having an inverse time limit, is

* For data on this subject see 'Low Voltage A.C. Networks,' D. K. Blake, *Gen. El. Rev.*, Vol. 31, p. 186.

another means of providing adequate protection during both starting and normal running.

(b) *Starting at Reduced Voltage.*—As explained in § 681, the effect of starting an induction motor at reduced voltage is to reduce the starting torque in proportion to the square of the voltage, e.g. halving the voltage quarters the starting torque. If the applied voltage be reduced by resistance in series with the primary (usually the stator) windings of the motor, the line current is reduced in the same ratio as the voltage across the motor terminals, but with star-delta or auto-transformer starting the line current is reduced in proportion to the square of the motor voltage. On the other hand, the P.F. of the motor when started with primary re-



(a) With Primary Resistance. (b) By Auto-transformer.

Fig. 347.—Comparing line currents when starting induction motors by different methods.

sistance is considerably higher than that of the motor with an auto-transformer.

Fig. 347 compares the two cases of starting with primary resistance and by auto-transformer respectively.

(a) *With Primary Resistance.*—The line current equals the motor current and, if the equivalent resistance (i.e. the impedance) of the motor is $z \Omega$, the voltage applied to the motor terminals is $v = Iz$ volts. Also, $v/E = Iz / I(R + z) = z/(R + z)$. The current $I = E/(R + z)$ amps. and, if the motor were started on full voltage (i.e. with $R = 0$), the current would be E/z amps., hence the use of series resistance reduces the line current in the ratio $z/(R + z)$, which equals v/E . In other words, the line current is reduced in the same ratio as the voltage applied to the motor.

(b) *By Auto-transformer.*—In this case, $Iv = iE$ (see also § 396, Vol. 2), and, if v is to be the same fraction of E as in case (a), we have $v = E z / (R + z)$, hence $IEz/(R + z) = iE$ and $i = Iz/(R + z)$. With full-voltage starting the current would be E/z as before and this equals $I(R + z)/z$ (for $v = Iz$ and also =

$Ez / (R + z)$. Hence the use of the auto-transformer reduces the line current in the ratio

$$\frac{I_z}{(R + z)} \cdot I(R + z)$$

In other words, the line current is reduced in proportion to the square of the voltage applied to the motor.

Starting by means of resistance in series with the stator is obviously wasteful (see Fig. 353), but is sometimes convenient where small squirrel-cage motors are concerned.* A motor which develops $1\frac{1}{4}$ times full-load torque with 6 times full-load current at full-voltage, will develop about $\frac{1}{2}$ full-load torque with 4 times full-load current, and from 0.1 to 0.25 times full-load torque with $1\frac{3}{4}$ to $2\frac{3}{4}$ times full-load current if started by means of primary (stator) series resistance.

The IR drop in the series resistance decreases as the motor accelerates and the current falls. There is consequently an automatic increase in the voltage applied to the motor and a greater increase in the torque developed (the latter varying with the square of the voltage). The motor, therefore, accelerates to a higher speed than it would on a constant reduced voltage (as given by an auto-transformer) of the same value as that initially given by the series resistance and the current rush following the short-circuiting of the resistance is relatively small because the IR drop in the resistance has already fallen to a low value; on the other hand, the initial line current is heavier, because it varies with the applied voltage instead of with the square of the latter.

In certain cases where motors of 10 to 20 H.P. are started by switching straight on to the supply at a distant station, the IR -drop in the leads, heavy at first and then automatically decreasing, retards the acceleration of the machines by starting them, in effect, through series resistance. In some instances, the size of the supply leads has been purposely reduced in order to intensify this effect. The IR loss in the leads during normal operation is, of course, increased at the same time. Also, the terminal voltage at the motor is reduced and this may result in overheating of the machine when loaded. Low voltage on induction motors running at or near rated load at the end of long and heavily loaded circuits is a common cause of overheating.

For small hoists, machine tools and other drives requiring motors up to 20 H.P. it is often convenient to use a drum-type stator-resistance controller giving four values of resistance, forward

* The method is equally applicable to slip-ring motors, but there is no point in using it; much better starting characteristics can then be obtained by means of variable resistance in the rotor circuit.

and reverse. The total resistance may be such that about half full-load torque is available on starting. Fig. 348 shows at

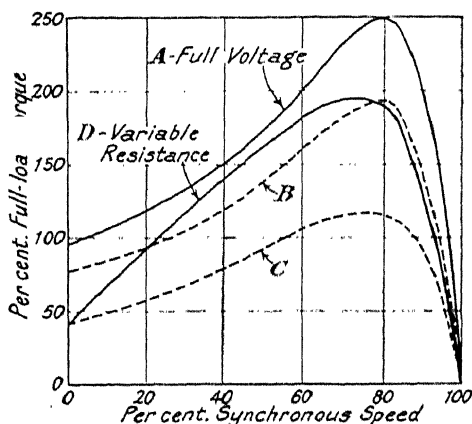


FIG. 348.—Torque-speed curves for induction motor started on full-voltage and with various values of primary resistance.

reactive instead of ohmic voltage drop (§ 45, Vol. 1); the PR loss is therefore much reduced, but, on the other hand, the P.F. is also considerably reduced. The current and torque characteristics are practically the same as when using series resistance for the same voltage reduction, but the energy dissipated in the starter is much less (see Fig. 353).

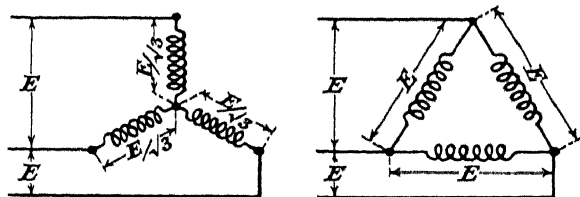


FIG. 349.—Applied voltages in star and delta connections.

Star-delta switching is one of the commonest methods of reducing the starting current of 3-phase squirrel-cage motors, *series-parallel switching* being the corresponding method for 2-phase motors. The applied voltage per phase when a 3-phase winding is connected in star is $1/\sqrt{3}$ or about 0.58 times that

corresponding to delta connection (see Fig. 349), hence the starting torque with star connection is one-third of that with delta connection. Also, the current taken from the mains with the windings in star is one-third that taken with the windings in delta. Thus, if a particular 3-phase squirrel-cage motor develops 0.8 times full-load torque with $5\frac{1}{2}$ times full-load current when it is started with its windings in delta, it will develop about 0.27 times full-load torque with 1.83 times full-load current when started with its windings in star. These conditions are shown in Fig. 350, from which also it will be seen that there is a heavy rush of current at the moment of changing over from star to delta connection when the motor has reached about 85 % of its synchronous speed. The low starting torque with the windings in star is the inevitable consequence of reducing the applied voltage. If the voltage be reduced to a less extent, say to 80 % of normal, by means of an auto-transformer, the starting torque is higher than with star-delta starting, but so is the starting current.*

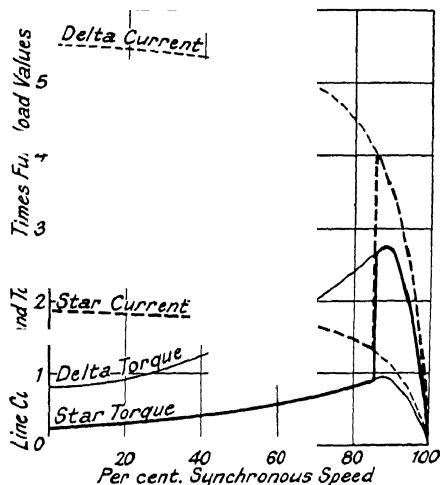


FIG. 350.—Current and torque curves for star-delta starting.

The current rush at the moment of changing from star to delta connection is undesirable, but it is less than the starting current in delta connection (4 as compared with $5\frac{1}{2}$ times full-load current in Fig. 350) and it lasts for a much shorter time, the motor being already nearly up to speed, and the current rush being accompanied by a large increase in torque, as shown. This momentary and comparatively moderate rush of current is not serious in a modern supply system.

Normally, a squirrel-cage motor, started by means of a star-delta switch, is changed over to the delta connection as soon as it has reached about 80 to 85 % of its

* It is of course possible to use a motor with inherently higher starting torque ; see Table 121, § 684.

synchronous speed, otherwise the maximum torque which can be developed remains relatively low (Fig. 350). If, however, it is known that the machine will operate for a considerable period at not more than half-load, the stator connections may be left in star. The maximum power which can then be developed is usually between 50 and 60 % of the rated output of the machine, but the power factor and efficiency of the motor are higher than they would be at the same load with the stator phases in delta connection. On light load the magnetising current, with the star connection, is about one-third of that flowing when the stator phases are connected in delta; and at one-third of full load the power factor of the star-connected machine is about equal to the full-load power factor with delta connection, say 0.85 instead of 0.65. Similarly, the efficiency of the star-connected machine at one-third load may be about 85 %, instead of, say, 80 %, with delta connection. There is thus considerable advantage in operating the motor with star-connected stator phases provided that the load will not exceed say 50 % of the rated output of the delta-connected machine; but it is obviously impracticable, or at least uneconomical, to run the machine in this way if frequent increases in load necessitate changing the connections to delta in order to prevent the motor from stalling.

Obviously, star-delta starting is only applicable to motors designed for normal operation with the stator windings in delta or mesh connection. The fact that star-delta starting is to be employed must be mentioned when ordering the motor.

An alternative method of starting induction motors at reduced voltage is by means of an *auto-transformer or compensator* (§ 396, Vol. 2). The advantage of this method, compared with star-delta switching, is that alternative tapplings can be provided corresponding to various pressures from, say, 40 to 80 % of line voltage. If a 65 % tapping be used, the starting torque and line current are $(0.65)^2$, i.e. about 0.42 of the values corresponding to full-voltage starting. The tapping used may be selected once for all to suit the particular motor and load concerned, choosing the lowest voltage at which the motor starts satisfactorily; or a special switch may be used (Fig. 112, § 396, Vol. 2) to enable progressively higher voltages to be applied. As the auto-transformer is only used temporarily it may be of the open-delta type (§ 394, Vol. 2), but a standard 3-phase auto-transformer is preferable on the whole. A typical arrangement is shown diagrammatically in Fig. 351. A mechanical device is sometimes used to ensure that the switch is moved quickly from the starting to the running position. Care should be taken that the connections between the running side of the switch and the motor are perfect, otherwise the machine, having been started regularly, will continue to run with single phase supply and will overheat on load (§ 681).

A squirrel-cage induction motor with a low-resistance rotor

takes about $6\frac{1}{2}$ times full-load current if switched straight on to the mains, the current falling to about four times full-load value by the time the motor has reached 80 % of synchronous speed (see Fig. 277, § 681). If the machine be started at reduced voltage, by means of a 'compensator' (auto-transformer), the current taken from the network at starting is reduced in proportion to the square of the voltage applied to the motor, e.g. halving the applied voltage reduces the current taken from the mains to one-quarter of the initial value (see Fig. 352). It must be remembered, however, that starting at reduced voltage also involves reducing the starting torque in proportion

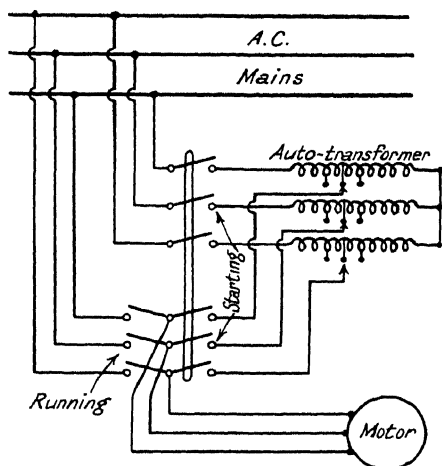


FIG. 351.—Starting squirrel-cage induction motor by auto-transformer.

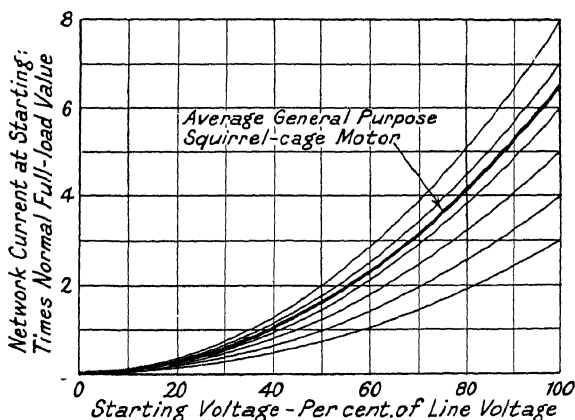


FIG. 352.—Starting current taken from network by squirrel-cage induction motors with various values of voltage applied to motor.

to the square of the voltage (§ 681). There is consequently the danger that, if the motor is started on too low a tapping of

the compensator, the torque will only be sufficient to bring it up to a fraction of the synchronous speed, with the result that there will be a very heavy rush of current when the compensator switch is thrown over, placing the motor on full vol

For example, if the motor takes $6\frac{1}{2}$ times full-load current when started on full voltage, the 50 % tapping on the compensator will reduce the starting current to $\frac{1}{4} \times 6.5$ or 1.63 times the full-load value (Fig. 352), but, if the torque is then only sufficient to bring the motor up to 75 % of synchronous speed, the current will rise to nearly $4\frac{1}{2}$ times full-load value when the motor is changed over to full-voltage (see Fig. 277). By using a higher tapping, say 65 % voltage, the starting current would be raised to about 2.7 times the full-load value, and the change-over current would be brought to about the same amount.

Where the motor starts on light load, so that the reduced torque consequent upon the low starting voltage still brings the machine nearly up to full-speed, a low tapping on the compensator may be used without an abnormal rush of current occurring when the full voltage is subsequently applied.

If a combined induction motor and lighting load has to be supplied through a relatively small transformer and a secondary circuit of high reactance it may be advisable to use resistance starters for the motors in order to avoid the voltage dip and lamp flicker which would occur under such circumstances if compensators were used to start the motors.

Owing to the limited starting torque of squirrel-cage motors when started by star-delta switching or by auto-transformer, they must be started on relatively light load, using a clutch if necessary to permit of this being done. A reliable automatic centrifugal clutch properly adjusted and installed is entirely satisfactory for motors up to 250 H.P. or so. The clutch should not engage the load until the motor has been changed over to the delta connection; thereafter, the motor is capable of exerting $2\frac{1}{2}$ to 3 times full-load torque without pulling out of step (Fig. 350) and can therefore start the load with certainty. The use of a motor specially designed to develop high starting torque (Fig. 277, § 681) may obviate the necessity for a clutch.

If the change-over from partial to full voltage (whether by star-delta or auto-transformer) is made automatically, it is safer to effect the change by a time-limit rather than a current-limit device. The net accelerating torque in the starting position may be low, owing to low supply voltage or heavy load, and dangerous heating may be caused before the current falls to the value at which the change to

full voltage would normally be made. If, however, the change-over be made after a definite time interval the worst that can happen is an abnormally heavy rush of current which will quickly decrease as the motor accelerates under the torque corresponding to full-voltage.

Star-delta switching or the use of auto-transformers avoids the I^2R loss associated with the use of starting resistance, whether in the primary or the secondary circuit.

The heat developed in the rotor is an important consideration in the starting of any squirrel-cage machine, whether the latter be an ordinary squirrel-cage induction motor or a synchronous motor started by means of a squirrel-cage winding. This heat energy is equal to 'the stored energy of the rotating parts at synchronous speed plus an amount represented by the area of a curve obtained by plotting the product of slip and load torque against time over the whole starting cycle.' In some actual cases* the kinetic energy of the rotating mass equals 80% of the total heat loss in the rotor; hence high inertia is liable to cause serious heating, particularly if starts be frequent, and it is impossible to reduce this by any change in the construction of the starting winding. Owing to the rapid rate of heat generation during starting, conduction into the iron is more effective than ventilation in keeping the temperature of the windings within bounds. This heating problem is more important the fewer the number of poles in the motor (*i.e.* the higher the r.p.m.), because the dimensions of the rotor for given horse-power are smaller the fewer the number of poles.

(c) *Starting by means of Additional Resistance in the Rotor Circuit.*†—This method of starting is inapplicable to squirrel-cage motors in which the rotor bars are permanently short-circuited; but it is used in some special types of squirrel-cage motors in which the effective resistance of the rotor circuit is reduced automatically when the machine has accelerated to a predetermined speed, by means of centrifugal switches which short-circuit resistances in the rotor or change the connection of groups of rotor bars from series to parallel.

Generally, however, starting by means of resistance in the rotor circuit is restricted to machines with phase-wound rotors, the rotor windings being connected to slip rings between which a variable external resistance is inserted (see, for example, Fig. 282, ignoring the compensating winding).

* *Vide* D. W. McLenegan and Ivan H. Summers, *Jour. Amer. I.E.E.*, Vol. 47, p. 587.

† It is here assumed that the secondary circuit is, as usual, on the rotor. The method is equally applicable to machines in which the primary is on the rotor and the secondary on the stator; the starting resistance is then inserted in the stator phases, as, for example, in Fig. 283.

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The effects of variable rotor resistance on the torque developed by an induction motor are fully discussed in § 681, in connection with Fig. 276.

The value of the starting resistance employed may be such as to develop maximum torque, or a higher initial resistance may be used in order to limit the value of the current. Step by step metal resistances may be used or liquid rheostats may be employed. It is usual to restrict the current peaks during starting to from 1.6 to 1.75 times the full-load current, the maximum torque developed being then about 1.6 times full-load torque. When the starting resistance has been completely removed, the brushes should be lifted and the slip rings short-circuited either automatically or by a manually operated switch, unless it be required to re-insert resistance in the circuit for purposes of speed control or to increase the slip temporarily so that advantage may be taken of flywheel storage.

Full voltage is applied to the primary (stator) when starting by resistance in the secondary (rotor).

Comparison of Methods.—Fig. 353, from a paper by C. W. Falls,* affords most instructive comparisons between the characteristics of a squirrel-cage motor started: *A*, on full voltage; *B*, by means of series reactance in the primary; *C*, by series resistance; and *D*, by means of an auto-transformer. In cases *B*, *C* and *D* the pressure applied to the motor was 70 % of the line voltage. All three methods of starting by reduced voltage give practically the same rate of acceleration (see torque curves), but the auto-transformer reduces the line current to a minimum and also involves less waste of energy than the other methods. The dotted curve in the loss chart shows the power consumed in the motor when starting at reduced voltage. With large, low-voltage motors it becomes difficult to dissipate the I^2R loss from a resistance starter, particularly if starting be frequent. A resistance starter is considerably cheaper than an auto-transformer, and its applicability to multi-step starting is an important advantage.

725. Speed Control of Polyphase Induction Motors.—As explained in § 681, the A.C. induction motor is inherently a

* Before the American Institute of Electrical Engineers; see *Power House*, Vol. 22, p. 39.

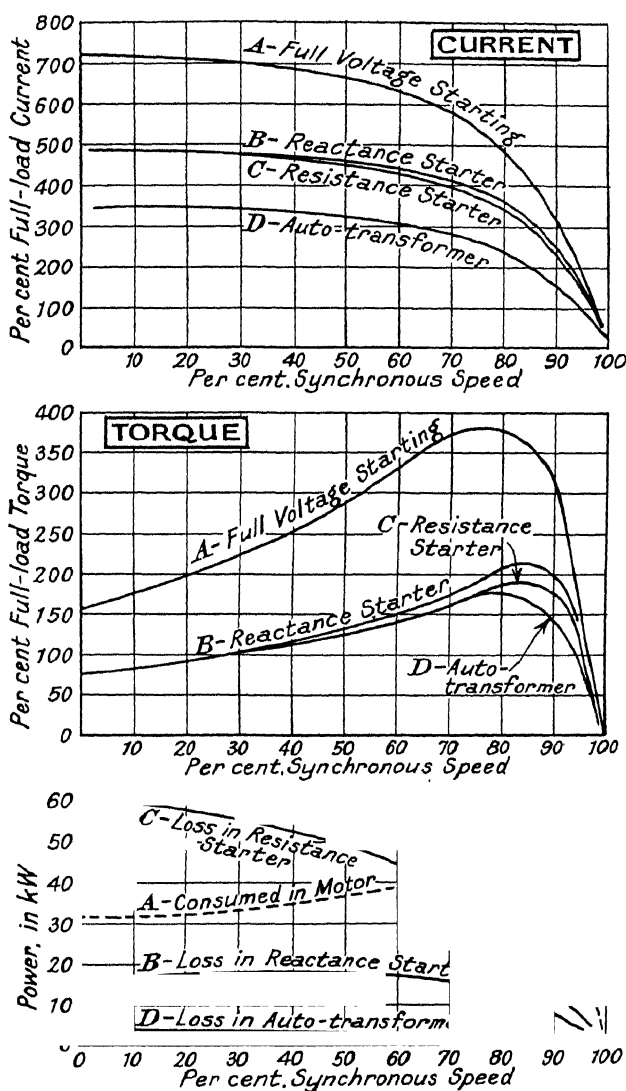


FIG. 353.—Characteristics of squirrel-cage induction motors started by different methods.

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machine of almost constant speed. Its synchronous speed is $60f/p$ r.p.m.; where f = supply frequency in cycles per sec., and p = number of *pairs* of poles in the primary (usually the stator). The actual speed of the machine is always less than the synchronous speed by the amount of the 'slip' (§ 681), which is almost zero on light load and seldom more than 5 to 8 % on full load unless it is deliberately increased for purposes of speed control.

Alternative methods of varying the speed of induction motors are therefore:—

(a) *By Changing the Frequency of the Supply.*—Theoretically this enables any desired speed to be obtained, but the method involves the use of a variable-speed generator or a regulable frequency-converter devoted specially to the supply of the motor concerned. Also, a motor designed for one frequency will not operate equally satisfactorily on widely differing frequencies (§ 135, Vol. 1).

(b) *By Changing the Number of Poles in the Primary.*—This can be effected by altering the connections of the winding, but it is obvious that the winding must be specially designed to make this possible; that considerable complication of connections and switchgear is involved; and that only definite and more or less widely separate speeds can be obtained, inversely proportional to the number of poles in each case.

(c) *By Changing the 'Slip.'*—The slip can be increased, i.e. the speed of the motor can be reduced, by inserting extra resistance in the secondary circuit (usually the rotor), but this involves additional I^2R losses and the actual speed varies to a greater extent with the load (see notes on Fig. 276, § 681). An efficient method of varying the slip is by means of an auxiliary machine which injects an E.M.F. of regulable frequency and phase into the rotor circuit of the main motor, thus controlling the speed of the latter above and below synchronism, and also providing for P.F. correction. The cost and complication of having two machines instead of one is a serious consideration where a low H.P. is concerned, but such combinations are very useful in high-power applications.

Cascade and variable speed sets are discussed more fully in § 727; while the following notes amplify the preceding remarks concerning speed regulation by variable frequency, pole-changing, and secondary resistance.

(a) *Speed Control by Variable Frequency.*—A wide range of speed control is possible if the frequency of supply can be varied. By this means speeds above or below the normal synchronous speed can be obtained without serious regulation losses, as in series resistance; also, the speed remains practically constant with each value of the supply frequency at all loads, whereas there is a marked fall in speed with increasing load when series resistance is employed. Unfortunately, an A.C. supply of variable frequency is not generally available, but it can be obtained by means of a frequency-changer. The use of a slip-ring induction motor as a frequency-changer for this purpose has been suggested,* and the method may be useful for temporary service which does not justify the purchase of a variable speed A.C. commutator motor.

An auxiliary motor is used to drive the rotor of the frequency-changing slip-ring motor at such speed that the frequency of the 'slip' current corresponds to the desired speed of the main driving motor, the latter being then supplied from the slip rings of the frequency-changer. According to the direction and speed of rotation of the frequency-changer rotor, frequencies above or below that of the normal supply can be obtained.

For example, if a 4-pole induction motor is to be run at 2 000 r.p.m., corresponding to a synchronous speed of, say, 2 100 r.p.m., it must be supplied at a frequency of $2\,100 \times 2/60 = 70$ cycles/sec.† Suppose that the frequency-changer is a 6-pole slip-ring motor. To obtain a slip frequency of 70 cycles/sec. in the rotor circuit of this machine, the rotor must be driven at a speed of $60 \times 70/3 = 1\,400$ r.p.m. *with regard to the synchronously rotating field of the stator.* The speed of this synchronous field is $60 \times 50/3 = 1\,000$ r.p.m. (assuming 50-cycle main supply), hence the frequency-changing rotor must be driven at $1\,400 - 1\,000 = 400$ r.p.m. *in the opposite direction to that in which it would run if the frequency-changer were allowed to operate as a motor.*

Under these conditions, the auxiliary motor must supply $\frac{4}{11}\frac{1}{10}\%$ or about $28\frac{1}{2}\%$ of the total input required by the main driving motor, the remaining $71\frac{1}{2}\%$ being supplied through the stator of the frequency-changer (plus losses in both cases).

The solution to other requirements may be worked out in the same way, the frequency-changing rotor being driven in the direction of the rotation of the stator field when a frequency lower than 50 cycles/sec. is required, so as to obtain a sub-synchronous speed in the main driving motor.

Theoretically, the H.P. of the main driving induction motor remains the same at all speeds obtained by this method, the torque

* 'A Speed Variation Scheme,' G. F. Heath, *El. Rev.*, Vol. 104, p. 145.

† The relation here employed is: Frequency, in cycles/sec. = r.p.m. \times No. of pairs of poles / 60.

varying inversely with the speed. The power factor and will usually be higher at speeds above the normal. The centrifugal stresses increase with the square of the speed, and it should be borne in mind that induction motors are not ordinarily intended for operation above rated synchronous speed. Indeed, they are incapable of so running unless supplied at higher than their rated frequency.

(b) *Speed Control by Pole-Changing.*—This method of control is best adapted to obtaining a limited number of speeds over a comparatively wide range, but it can be combined with secondary

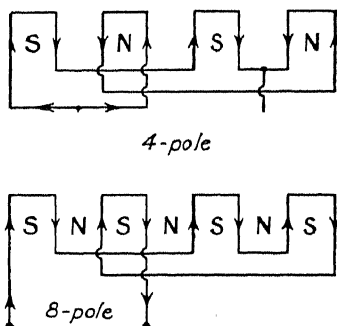


FIG. 354.—Illustrating principle of pole-changing winding.

resistance control (*see (c)* below) to obtain intermediate speeds. The principle of the method is illustrated by Fig. 354. In the upper diagram four poles are produced by circulating current in opposite directions round two groups of stator coils in parallel. In the lower diagram all the coils are in series and the direction of current flow is the same in each; four South poles are therefore produced within the coils and this results in the formation of North 'consequent' poles between them, *i.e.* there are eight poles in all, and the synchronous speed of the motor is halved. The same principle is applicable to obtaining other combinations in one or more stator windings. If the rotor is of the squirrel-cage type it operates satisfactorily regardless of the number of poles in the stator, but, if intermediate speed regulation is to be obtained by variable rotor resistance, a slip-ring rotor must be used and provision must be made for changing the number of rotor poles to suit the number of poles in the stator. This involves much extra cost and complication, but speed control by rotor resistance can be obtained from any one speed (preferably the maximum speed, corresponding to the smallest number of stator poles) without changing the number of rotor poles. In order to pass from one speed to another without undue current rush, resistances may be placed in series with the stator during the transition. The sequence of more or less involved changes in connection in a pole-changing motor

is usually effected by a drum-controller, or by contactors actuated by a master controller of the drum type.

Speed control by pole-changing is stable, *i.e.* independent of the load except for the small variation in slip, and there are no I^2R regulating-losses comparable with those of speed control by rotor resistance, but the efficiency and power factor of the motor are appreciably lower when the windings are connected for the higher number of poles, *i.e.* for the lower speed (see Table 132 and Fig. 355).

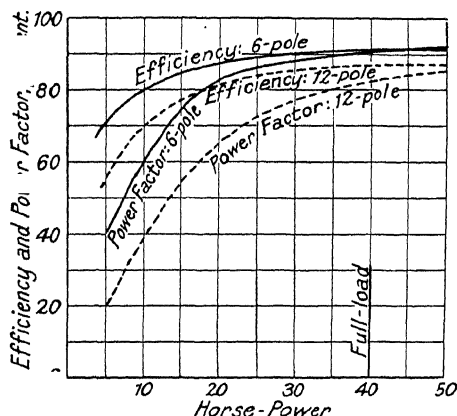


FIG. 355.—Efficiency and power factor of pole-changing induction motor (6/12 poles) at various loads.

TABLE 132.—*Typical Data for Squirrel-Cage Induction Motor with Pole-Changing Stator Windings.*

No. of Poles in Stator Winding.	Syn-chronous Speed on 50-Cycle Supply. R.P.M.	Rated Output and Speed.		Efficiency, Per Cent. at				Power Factor at			
		H.P.	R.P.M.	Full-Load.	$\frac{3}{4}$ Load.	$\frac{1}{2}$ Load.	$\frac{1}{4}$ Load.	Full-Load.	$\frac{3}{4}$ Load.	$\frac{1}{2}$ Load.	$\frac{1}{4}$ Load.
4	1 500	3	1 418	86	87	85	70	0.94	0.90	0.80	0.60
6	1 000	2 $\frac{1}{2}$	980	83	84	83	75	0.85	0.76	0.65	0.45
8	750	1 $\frac{1}{2}$	670	75	80	80	72	0.85	0.80	0.65	0.45

Creedy has devised a method of pole-changing by varying the phase between adjacent coils of a single winding, using, for this

purpose, a special auto-transformer.* Fig. 356 gives a general comparison between the efficiency of speed control by a Creedy pole-changing and rotor-resistance respectively. It must, of course, be remembered that the pole-changing motor operates only at a number of definite speeds (six in Fig. 356, as indicated by the dots), unless rotor-resistance is used for intermediate regulation. Provided that the restriction to definite speeds is acceptable, the constant-torque characteristic of the multi-speed induction motor (giving H.P. proportional to speed) is often closer to the requirements of the load than is the characteristic of the variable-speed

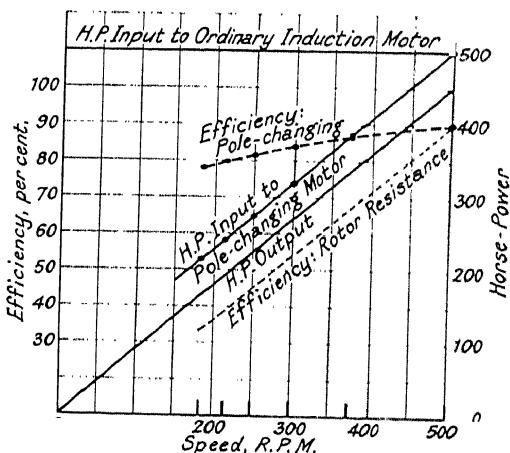


FIG. 356.—Comparing speed control of induction motors by pole-changing and rotor resistance.

D.C. shunt-wound motor (torque approximately inversely proportional to speed, hence H.P. approximately constant at all speeds).

(c) *Speed Control by Changing the Slip (using Variable-Resistance in the Secondary).*—The principle of speed control in wound-rotor induction motors by varying the total resistance of the rotor circuit will be evident from the notes on Fig. 276, § 681. If the resistance of the short-circuited rotor winding corresponds to the curve $R = 2$, the stable portion of the torque-speed curve is from O to A' and the motor will run at 60 % of its maximum (pull-out) torque, i.e. at about $1\frac{1}{2}$ times full-load torque with about 7 % slip. If the total resistance of the rotor circuit be increased

* *Electrician*, Vol. 78, p. 544.

so that the motor operates on the curve $R = 5$, the slip will be about 17 %. when the motor is developing the same torque as before, *i.e.* the machine will operate at S' instead of S (Fig. 276). The speed at other values of torque is reduced in the same way, but unfortunately the regulation is not stable, *i.e.* the speed for a given value of resistance varies with the load on the machine, and to a greater extent the higher the resistance used; also, the additional resistance in the rotor circuit involves a serious sacrifice of efficiency. If the method is adopted in spite of these disadvantages, up to 50 % or so reduction in speed can be obtained at full load by increasing the series resistance, but this is about the limit; any further increase in resistance would make operation extremely unstable, a small change in load then producing prohibitive variation in speed (see Fig. 276); also, the motor would be pulled up by a relatively small overload.

Fig. 357, which is deduced from Fig. 276, § 681, shows the effect of increasing the resistance in the rotor circuit on the speed of the machine at various loads. The speed decreases in direct proportion

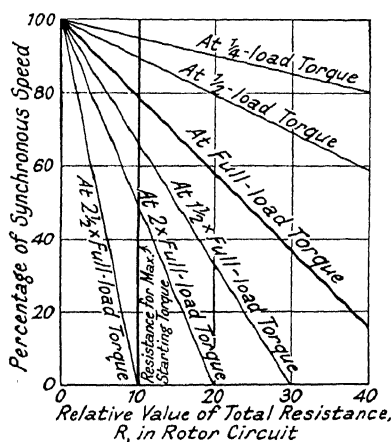


FIG. 357.—Showing effect of resistance in rotor circuit of induction motor on speed at various loads.

to the increase in resistance as long as the load-torque remains constant, but the variation in speed with increasing load rises rapidly as the resistance increases. At small values of total resistance, such as correspond to a short-circuited rotor (say $R = 1$ to 2, Fig. 357), the total variation of speed with load is not serious, say 6 % from $\frac{1}{2}$ to $1\frac{1}{2}$ times full-load torque; but for high values of R , such as required to reduce the speed to 60 % on full-load, the speed varies widely with the load, say from 80 % of synchronous speed at $\frac{1}{2}$ -load to about 36 % of synchronous speed at $1\frac{1}{2}$ -load. The regulating resistance must, therefore, be continually adjusted to maintain constant speed if the load is variable.

The other objection to speed control by variable rotor resistance

is illustrated by Fig. 356; the input to the motor remaining constant, for constant torque, the output decreases in direct proportion to the speed. The difference between the input and output is mainly dissipated in the regulating resistance, and the efficiency of the machine falls rapidly as the speed is reduced. When the torque required by the load decreases with speed, as in the case of fans and centrifugal pumps, the loss in the regulating resistance at reduced speeds is relatively less than in the case of a constant-torque load, but is still serious; see Table 134, § 726.

Owing to inefficiency and instability of speed control by rotor-resistance this method is mainly restricted to such applications as haulage motors under continual manual control, and to the use of 'slip regulators' in conjunction with flywheel storage. For this purpose, a high-resistance rotor winding might be used, giving a high value of slip, but this would involve correspondingly high I^2R losses in the rotor during the whole time the motor was in service. Obviously it is more economical to insert supplementary resistance in the rotor circuit as and when it is desired to utilise the flywheel effect. This can be done automatically,* the slip-regulator inserting resistance progressively as the load exceeds a predetermined value. The temporary increase in the I^2R loss is justified by the convenience of this method of drawing upon the energy stored in the flywheel.

The speed of an induction motor can only be *reduced* by inserting additional ohmic resistance in its rotor circuit; if, however, a suitable E.M.F. be injected into this circuit by means of an auxiliary machine (§ 727), the effect of a negative resistance can be obtained, *i.e.* speeds *above* the normal value can be reached and, at all speeds, the losses of regulation by ohmic resistance are avoided.

Switchgear for the reversal of a polyphase induction motor and speed control by rotor resistance comprises a reversing switch or contactors in the stator circuit, and step-by-step rheostats with drum controller or liquid rheostats in the rotor phases. Suitable interlocks should be provided to ensure that some (and preferably all) of the rotor resistance is placed in circuit again whenever the

* Say by a servo-motor (*e.g.* a torque induction motor, applying variable torque without continuous rotation), which is supplied through a current transformer in the stator circuit of the main motor. When the load on the main motor exceeds a predetermined value, the auxiliary motor inserts resistance in series with the main rotor, increasing its slip and allowing the flywheel to assist the main motor.

motor stops, for whatever reason. Press-button control may be used to operate start-stop contactors in the stator circuit, and to start in one direction or the other a servo-motor which inserts resistance in or removes it from the rotor circuit.

TABLE 133.—*Approximate Full-Load Rotor Currents of 3-Phase Slip-Ring Induction Motors (Ellison).*

NOTE.—Where no idea exists whether the motor will be in the low or the high group, the value in col. 4 may be taken as a bad approximation. If at all possible, the exact figure should be obtained from the makers of the motor.

Open circuit rotor volts are easier to obtain by measurement on site and, if 850 W per B.H.P. be allowed, a sufficiently close approximation to the true full-load rotor current is obtained.

1.	2.	3.	4.	5.	6.
B.H.P. of Motor.	Minimum Amperes.	Maximum Amperes.	Average of Min. and Max. Amperes.	Average of Min. Group Amperes.	Average of Max. Group Amperes.
5	12.5	74	43.25	20.0	65
10	17.5	90	53.75	27.5	70
15	25.0	104	64.5	32.5	76
20	35.0	110	72.5	40.0	82
30	37.5	128	82.75	47.5	95
40	45.0	140	92.5	55.0	105
50	50.0	160	105.0	65.0	120
60	54.0	160	107.0	70.0	128
70	58.0	185	121	77	130
80	63.0	198	128	82	140
90	76.0	196	136	90	145
100	95	200	147	100	155
110	105	200	152	110	162
120	118	200	159	125	170
150	160	210	185	—	—
200	190	230	210	—	—
300	200	320	260	—	—
400	200	400	300	—	—

The rotor current of a slip-ring motor varies widely with the design of the machine. Table 133* shows the extreme range that has been found to exist by an analysis of motors by eight well-known firms. The fourth column shows the average of the extreme

* Abridged from a useful brochure 'Hints on Rectifying Faults in Motor Control Gear,' issued by the firm of George Ellison, Birmingham.

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values in columns 2 and 3. The fifth and sixth columns show the averages for the low-current and high-current groups respectively.

726. Methods of Speed Control Compared.—Table 134* affords an interesting comparison between various methods of varying the speed of a mine fan. It is assumed that the power

TABLE 134.—*Comparison between Methods of Speed Control.*

	Fan Speed, R.P.M.			
	400.	300.	200.	180.
Per cent. of maximum speed . . .	100	75	50	32.5
Power absorbed by fan, in H.P. . .	350	148	44	12
" " " in kW . . .	261	110	33	9
(1) <i>Induction motor with variable rotor resistance.</i>				
Input to motor, in kW . . .	282	160	83	53
Efficiency, per cent. . . .	92.5	68.8	39.3	17.0
Power factor	0.77	0.63	0.4	0.2
(2) <i>Pole-changing squirrel-cage motor.</i>				
Input to motor, in kW	294	182	46	—
Efficiency, per cent.	89.0	84.0	71.0	—
Power factor	0.74	0.52	0.28	—
(3) <i>Brush-shifting A.C. commutator motor.</i>				
Input to motor, in kW	296	140	45	20
Efficiency, per cent.	88.0	78.6	72.8	44.8
Power factor	0.95	0.93	0.50	0.33
(4) <i>D.C. motor supplied by variable-voltage synchronous motor-generator.</i>				
Input to motor-generator, in kW .	326	148	60	35
Overall efficiency, per cent. . .	80.0	74.2	55.0	25.6
Power factor		Adjustable to 1.0 or leading value.		

absorbed by the fan varies with the cube of its speed so that at low speeds the motor is running at low H.P. as well. The drives compared are: (1) Wound rotor induction motor with variable rotor resistance. (2) Pole-changing squirrel-cage induction motor. (3) Brush-shifting A.C. commutator motor, changing from star to delta connection in the stator at high speeds. (4) D.C. motor with

* Based on data given by B. W. Chadbourne, *Coal Age*, Vol. 25, p. 722. The fan in question is a 160-in. machine normally running at 400 r.p.m. to deliver 200 000 cu. ft. of air per min. against 4-in. water gauge.

variable-voltage supply from a motor-generator set driven by an A.C. synchronous motor.

A variable-speed transmission of the hydraulic type can often be used to advantage where continuous variation of speed is required over a very wide range. Any desired speed, from crawling up to full speed forward or reverse, can be obtained; the mechanical efficiency is high (about 90 %); and the method often permits a squirrel-cage motor to be used with line voltage or star-delta starting.

727. Cascade Control.—Cascade combinations of two induction motors are mainly restricted to high-power applications, such as colliery winding, haulage, fans, and traction service. The simplest

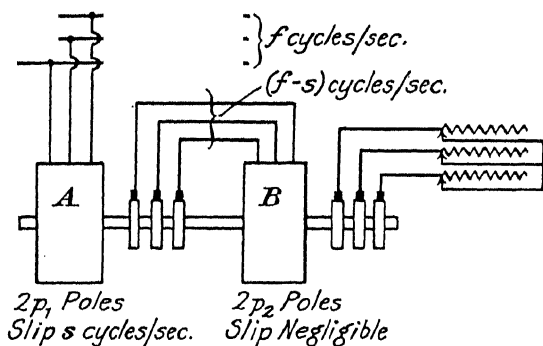


FIG. 358.—Illustrating cascade control of induction motors.

arrangement is shown diagrammatically in Fig. 358. Two motors, with p_1 , p_2 pairs of poles respectively, are coupled mechanically, and the stator of the second machine is fed from the rotor of the first. The synchronous speed of machine A when running alone on the main supply frequency f cycles/sec. is $60f/p_1$ r.p.m. Suppose that its slip frequency is s cycles/sec. when the two motors are running in cascade; * the speed of the motor A will then be $60(f-s)/p_1$ r.p.m. The motor B is supplied at frequency s cycles/sec. and, neglecting its slip, which will be only a few per cent. when the resistance R is cut out of circuit, the speed of B will be $60s/p_2$ r.p.m. But A and B must run at the same speed, as they are mechanically coupled, hence $60(f-s)/p_1$

* The percentage slip of the motor A will then be $100 s/f$ %.

$= 60s/p_2$. Solving this equation we have $s = fp_2/(p_1 + p_2)$; hence the speed of B ($= 60s/p_2$) $= 60f/(p_1 + p_2)$ r.p.m. and this is also the speed of A . The motor B may be used alone, its speed being then $60f/p_2$ r.p.m., but, if this is to be done, the stator of B (and therefore the rotor of A) must be wound for the main supply voltage. Finally, if B be connected so that it tends to run in the opposite direction to A , we have

$$60(f - s)/p_1 = -60s/p_2,$$

whence the speed of the combination $= 60f/(p_2 - p_1)$ r.p.m. If, as is usual, the number of poles in B is fewer than in A , p_2 is less than p_1 and a negative speed is obtained, i.e. the set runs in the opposite direction from that in which the motor A runs when used alone. This can be corrected by reversing the phase sequence of the supply to A , as well as the phase sequence of the cascade connection between A and B .

It will be seen that the speed of the *direct* cascade combination depends only on the *sum* of the numbers of poles in the two machines, regardless of how this sum is made up; whereas a *differentially* cascaded combination gives the same speed as long as the *difference* between the numbers of poles is constant. These points are illustrated by Table 135.

TABLE 135.—*Typical Cascade Combinations.*

(All speeds in this table relate to main supply at 50 cycles/sec.)

	No. of Poles in		Motor A Used Alone. R.P.M.	Motor B Used Alone. R.P.M.	Speed of Cascade Com- bination.	
	Motor A ($= 2p_1$).	Motor B ($= 2p_2$).			Direct Cascade. R.P.M.	Differential Cascade. R.P.M.
$(p_1 + p_2)$ constant	10	2	600	3 000	500	750
	8	4	750	1 500	500	1 500
	6	6	1 000	1 000	500	—
$(p_1 - p_2)$ constant	10	6	600	1 000	375	1 500
	8	4	750	1 500	500	1 500
	6	2	1 000	3 000	750	1 500

Two similar induction motors used in direct cascade connection run at half the speed of either machine used alone. The total torque developed by the combination is practically double that of

either motor used alone, hence the H.P. of the set equals that of a single motor at full speed.

If the second motor be belted or geared to the first, so as to run at n times the speed of the latter, the speed of machine A , with direct cascading, is $60f / (p_1 + np_2)$ r.p.m. while that of machine B is n times as great.

The fact that the magnetising current for machine B has to be supplied through machine A causes the P.F. of a cascade set to be low, say 0.5-0.7 compared with 0.8-0.9 for the individual machines. On the other hand, the P.F. of a cascade set may be higher than that of a single machine for the same low speed as the cascade combination. In large cascade sets a phase advancer is commonly used in the rotor circuit of the second machine.

Insertion of variable resistance in the rotor circuit of the second machine, so that the slip of machine B (Fig. 358) is no longer negligible, permits the speed of the set to be varied, but the speed then varies with load and the rheostatic loss is serious, as in the case of an ordinary slip-ring motor.

Many elaborations of the simple cascade combination have been evolved, particularly by arranging to change the numbers of poles in the individual machines so as to obtain additional speeds. Also, single multi-speed motors have been developed with special windings operating on the cascade principle.*

728. Variable-Speed Sets: Induction Motor with Auxiliary Machine.—These sets are applicable to, and generally restricted to high-power duties such as the driving of rolling mills, high-power pumps, fans, hoists, etc. For low and medium powers, A.C. commutator motors are generally more convenient and economical. The variable-speed induction motor set, however, can be used in sizes up to the maximum for which the induction motor itself can be built; the capital cost is relatively low and the efficiency relatively high because the auxiliary machine or machines deal only with the 'slip energy,' *i.e.* with the energy corresponding to the E.M.F. and current produced by the slip of the rotor of the main motor. As compared with cascade combinations of induction motors, variable-speed sets offer the important advantage of continuous speed control.

* For further particulars of these see L. J. Hunt, *Jour. I.E.E.*, Vol. 52, p. 406, and F. Creedy, *ibid.*, Vol. 61, p. 309.

If the frequency of the main supply and the number of poles in the main induction motor be fixed, the only method of varying the speed of the latter is by changing its slip. The object of the 'variable-speed set' is to vary the slip of the main motor and apply the slip energy to some useful purpose instead of causing it to be dissipated as heat, as is the case when the slip is varied by means of ohmic resistance in the rotor circuit. In some systems the auxiliary machine is also used to improve the P.E. of the main motor by supplying a suitable magnetising current to the rotor of the latter. The main motor must be of the wound-rotor (slip-ring) type.

Either of two main principles may be employed: (1) The slip energy may be converted to mechanical energy by the auxiliary machine. If this energy be added to the shaft of the main motor,* the horse-power of the combination remains practically constant, the H.P. of the auxiliary machine increasing as that of the main motor decreases. The total torque is, therefore, greater as the speed is reduced. (2) The slip energy may be converted to electrical energy at line voltage and frequency and returned to the supply system. The main motor alone then drives the load; the torque is constant and the H.P., therefore, decreases with the speed. This arrangement has the advantage that the auxiliary motor may be a high-speed machine instead of having to operate at the speed of the main motor, which is often very low; on the other hand, an extra auxiliary machine and an extra conversion of slip energy are generally involved.

Either of the two purposes—constant H.P. or constant torque driving—may be effected by using as the auxiliary part of the set a polyphase commutator motor (Scherbius system); a rotary converter (Krämer system); or, a frequency-changer. An exceptionally clear diagrammatic representation of the three main methods available under each principle of operation is given in Fig. 359.† In each case only one conductor is shown for each circuit. The following notes amplify the brief explanations given above.

* It may be more convenient in practice to utilise the mechanical output of the auxiliary machine to drive some other than the main load (e.g. a latex stand of rolls in a continuous rolling mill). The main motor then operates at constant torque, as in case (2), but the sum of the horse-powers of the main and auxiliary motors remains constant, neglecting conversion losses.

† From 'Developments in Electric Drives for Rolling Mills,' by L. A. Umansky, *Jour. Amer. I.E.E.*, Vol. 46, p. 885.

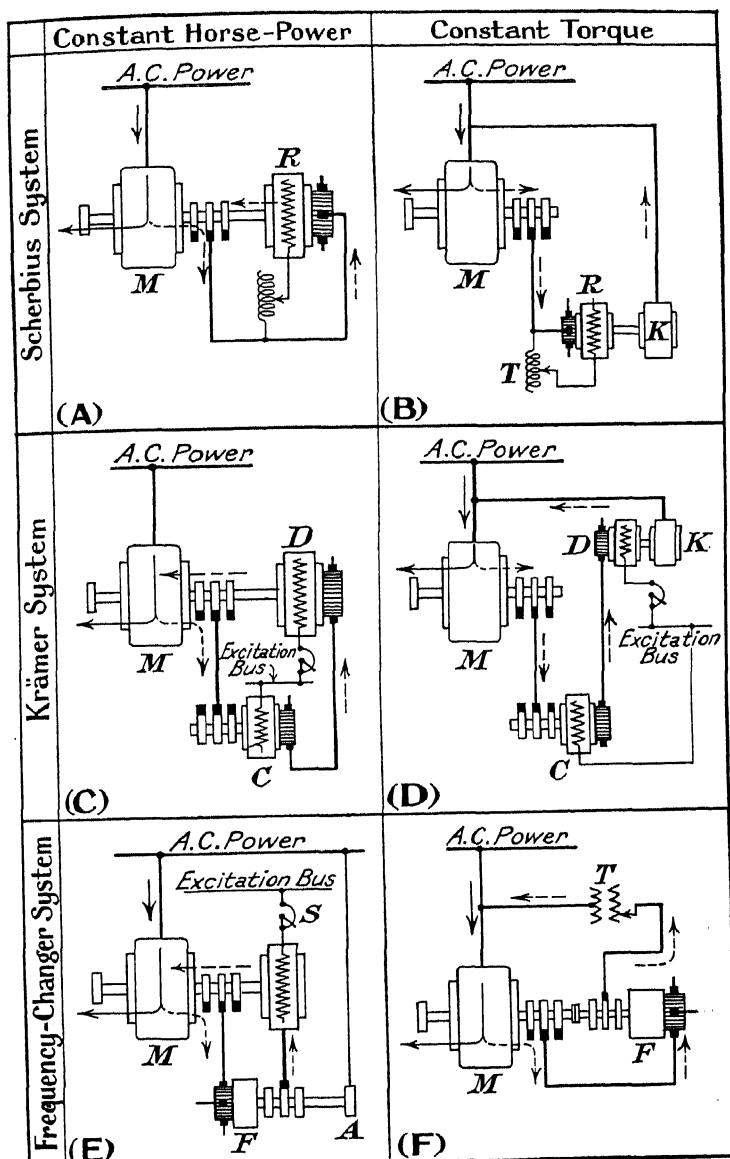


FIG. 359.—Variable-speed sets; induction motor with auxiliary machine or machines.

Scherbius System.—An auxiliary polyphase commutator motor R is either mounted on the main driving shaft so as to add its mechanical output to that of the main motor (Fig. 359 (A)), giving a constant-H.P. drive; or R drives an induction generator K , which feeds electrical energy back to the main supply system (Fig. 359 (B)), a constant-torque drive being now obtained on the main motor shaft. The shunt-wound machine R is excited from the slip-rings of the main motor and, by varying its excitation, the slip of the main motor can be adjusted. Speeds above or below synchronism are obtainable, but when the set is running above synchronism the direction of flow of the slip energy (dotted arrows) is reversed; the machine R then absorbs some of the power developed by M in Fig. 359 (A), and draws power from the main supply in Fig. 359 (B). By providing compensating windings on the motor R , the P.F. of the main motor can be regulated. From 40 to 50 % speed variation is commonly obtained by this system. If the speed of the main motor is very low, it is economical to use the constant-torque arrangement, the combination RK (Fig. 359 (B)) being then a high-speed set.

Kr mer System.—The slip energy is converted to D.C. by a rotary converter C and the variable-voltage D.C. power obtained is fed to a motor D which is either on the main driving shaft (Fig. 359 (C)), or which drives an induction generator, restoring energy to the main A.C. supply system (Fig. 359 (D)). In either case the speed of M is controlled by varying the excitation of D , and speeds above or below synchronism can be obtained, the flow of slip energy being reversed, as before, when hyper-synchronous speeds are obtained. The P.F. of the main motor can be improved (up to about 0.9) by increasing the excitation of the converter C . Automatic decrease in speed with increasing load is obtained by compounding the motor D . It will be seen that this system requires one more auxiliary machine than the Scherbius system; also, the operation of the rotary converter is not stable at very low frequencies of the slip current, hence this system is generally restricted to speeds at least 10 % above or below synchronism.

Frequency-changer System.—In Fig. 359 (E) the frequency-changer F , driven by a small synchronous motor A (fed from the main supply), transfers the slip energy to a synchronous motor S on the main driving shaft. Regulating the excitation of S changes the speed of the main motor, while regulating the excitation of A

varies the P.F. of the main motor. In Fig. 359 (F) the frequency-changer is on the main driving shaft and its output, converted to the frequency of the main supply, is returned to the mains through the regulating transformer *T*; this arrangement eliminates the two synchronous motors used in Fig. 359 (E). Speed regulation is obtained by means of a variable auto-transformer between *M* and *F*. Speeds above or below synchronism can be obtained, the flow of slip energy being reversed, as in the preceding systems, when hyper-synchronous speeds are reached.

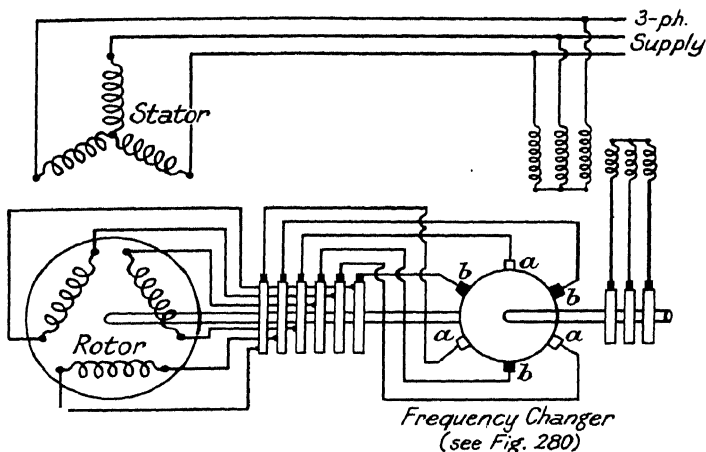


FIG. 360. -Speed regulation of induction motor by means of brush-shifting frequency-changer.

Fig. 360 illustrates the use of a brush-shifting frequency-changer to control the speed of a slip-ring induction motor. The main-rotor phases are connected separately through slip-rings to corresponding brushes in the two sets *a*, *b* of a frequency-changer of the type described in § 687 (Fig. 280). By varying the angle between the two sets of brushes, the E.M.F. applied to the rotor can be adjusted and speeds above or below synchronism can be obtained at will. The action of the frequency-changer is such that the supply frequency is always changed to the frequency of the slip current in the main rotor. P.F. correction can be obtained by phase displacement of the whole set of brushes *a*, *b*.

In all the above systems, the main motor is started by series resistance in the rotor circuit (like an ordinary slip-ring motor),

a change-over switch transferring the leads from the slip-ring brushes from the starting resistance to the auxiliary machine after starting has been completed.

Whenever possible, the total range of speed regulation desired should be equally divided *above and below synchronism*. Larger and more costly auxiliary machines are required to give 20% speed variation below *or* above synchronism, than to give 10% variation below *and* above synchronism, the total range of speed variation being the same in both cases.

Generally, the effect of the auxiliary speed-regulating machine or set is to give the main induction motor the speed characteristics of a variable-speed D.C. shunt-wound motor, *i.e.* any desired speed, within the range of regulation, is maintained nearly constant at

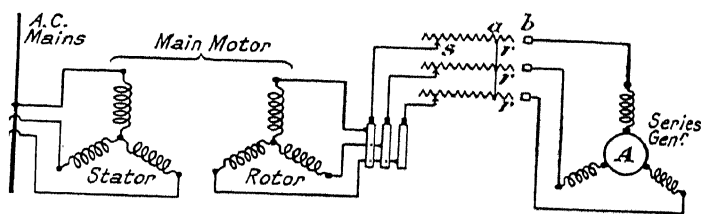


FIG. 361.—Variable-speed set; induction motor with series generator.

all loads. If desired, however, automatic compounding can be arranged, so that advantage can be taken of flywheel storage.

Fig. 361 shows the use of a series-wound A.C. commutator machine to control the speed and P.F. of an induction motor. The auxiliary machine differs only from the "negative inductance" (Fig. 279, § 687) in that it has field coils in series with its brushes. The main motor is started (and, if necessary, run) as an ordinary slip-ring induction motor. The contacts *b* are beyond the position *a* in which the starting resistance is short-circuited so that, when the starter *s* passes from the end of the resistance to *b*, the series generator is short-circuited through the resistances *r*; this ensures the excitation of the auxiliary machine. The series generator may be direct-coupled to the main motor or driven independently; in the latter case, it is necessary to safeguard the series generator from racing in the event of the supply to its driving motor being interrupted.

The E.M.F. generated in *A* is produced by the resultant of the

field due to the series field coils and the field due to the armature winding, both these fields rotating at a speed proportional to the frequency of slip in the main rotor. In addition there is an E.M.F. induced in the field coils by the resultant field of the armature. By shifting the brushes the E.M.F. at the terminals of the series generator, *i.e.* the E.M.F. applied to the main rotor, can be varied in magnitude and phase, thus giving speed control above and below synchronism and P.F. correction at all loads.

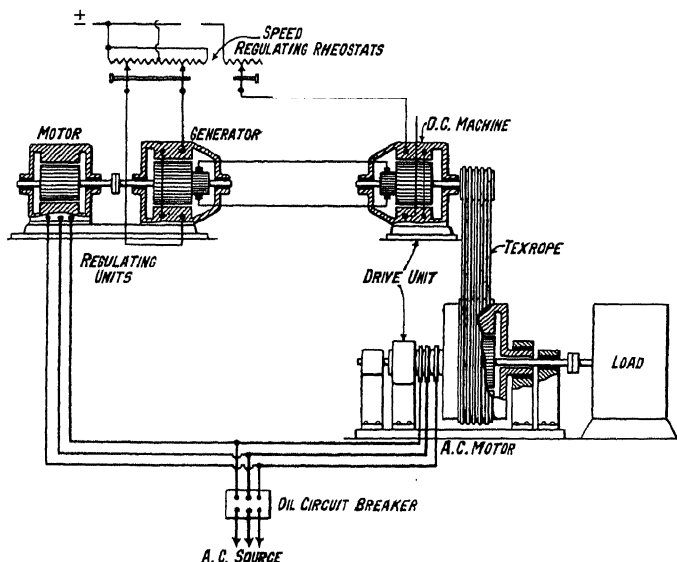


FIG. 362.—Speed control of induction motor by means of a variable-speed D.C. motor driving the stator of the A.C. machine.

729. Variable-Speed Sets: Induction Motor with Driven Stator.—Fig. 362 shows the essential features of a method for controlling the speed of an A.C. induction motor by means of a D.C. auxiliary motor and a motor-generator regulator set.* The rotor of the A.C. induction motor is supplied from the A.C. mains; and the stator, which is also mounted on bearings, is rotated in either direction at will by a multiple rope drive from

* This method was described by A. M. Rossman before the American Institute of Electrical Engineers, see *Jour. A.I.E.E.*, November, 1930, p. 930; also *Power Engineer*, January, 1931, p. 38, whence Fig. 362 is reproduced.

the D.C. motor in the 'drive unit.' This D.C. motor is a variable-speed machine supplied from the motor-generator set which operates on the Ward-Leonard principle (§ 716). The speed of the induction motor rotor with regard to its stator is constant, except for the small increase in slip with increasing load, but the speed of the stator can be varied continuously from a maximum in one direction to an equal value in the other direction by means of the auxiliary D.C. motor. The actual speed of the A.C. rotor, and of the load coupled thereto, is thus variable continuously over a wide range above and below synchronism. In typical cases, the capacity of the D.C. part of the drive unit ranges from 8.4 % of the whole with a speed range from maximum to 80 % to 23.5 % with a speed range from maximum to 10 %. There are losses in the motor-generator set and in the auxiliary D.C. motor, but no rheostatic losses. In a certain case, with a speed range from 708 to 282 r.p.m. at the load, the overall efficiency was 78.3 % at minimum, 88.6 % at middle, and 88.4 % at maximum speed. This method of control is particularly useful in connection with induction motors driving boiler fans and feed pumps. It is equally applicable to induction and to synchronous motors.

730. Control of Single-Phase Induction Motors.—The single-phase induction motor has no starting torque as long as it is a purely single-phase machine (see Fig. 366). Single-phase induction motors of fractional H.P. (say $\frac{1}{4}$ H.P. or less) can be started by giving them a spin with the fingers, after which they will pick up speed on light load. Larger machines can be started in similar manner by means of a pony motor but, to make a single-phase induction motor self-starting, it must be converted temporarily into a polyphase machine, so that a more or less symmetrical rotating field is produced during the starting period. This may be effected by: (a) pole-shading or other inductive device; (b) phase-splitting; (c) monocyclic device.

(a) *Pole-Shading, etc.*—In this method, a part of each stator pole is encircled by a copper ring or a few turns of heavy wire. The current induced in this circuit by transformer action causes the flux to lag in the part of the pole concerned. A resultant rotating field is established and the machine is self-starting, but with very small torque; also there are circulating currents and therefore losses in the shading rings during the whole time the motor

is running. For these reasons, the method is practically restricted to small fan motors and other motors of fractional H.P.

The same principle may be applied, with better results, by using a second distributed winding on the stator, as an 'accelerating coil.' This is short-circuited directly or through suitable impedance during the starting period, and thereafter open-circuited so that there may be no loss in it during normal running.

(b) *Phase-Splitting*.—By passing single-phase current through two circuits in parallel, and introducing extra inductance or capacity into one branch, there is obtainable a difference of phase between the currents in the two branches. This method of providing a form of 2-phase current may be applied to the provision of a rotating

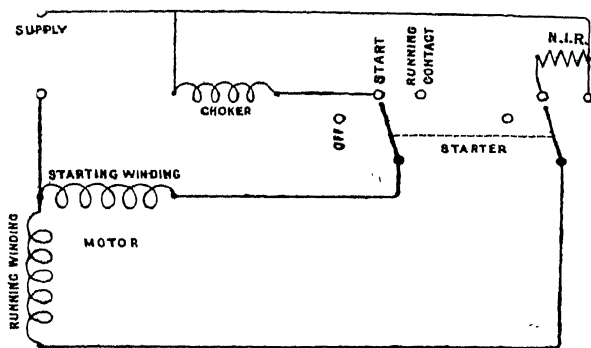


FIG. 363.—Field circuit of single-phase motor.

field in single-phase motors on starting, by the means indicated in Fig. 363. This diagram represents the stator and starter of a single-phase motor, the rotor being omitted. There are two stator windings, and, with the double-pole switch in its starting position, there is a non-inductive resistance (N.I.R.) in series with one winding and a choker in series with the other. Both resistance and choker reduce the current rush on starting and produce sufficient phase displacement between the currents in the two stator sections to yield a rotating flux and considerable starting torque. When the machine is up to speed, the switch is moved on to its running contacts, placing the running winding straight across the mains and disconnecting the starting winding altogether. To reverse rotation, the connections of either the starting or the running winding (but not both) are reversed; the same result may

be obtained by transposing the choking coil and the non-inductive resistance. In very small motors the resistance is sometimes dispensed with, but one must be obtained and fitted if this method of reversal is to be used; otherwise the starting coil might burn out.

Higher starting torque may be obtained, but at lower efficiency (*i.e.* with greater current demand for given torque), by running the whole stator winding permanently in series across the mains and connecting a choking coil and a non-inductive resistance *in parallel* with its two sections whilst starting. Subsequently, the shunt circuit is opened and the whole stator winding remains operative. Yet higher starting torque is obtainable by providing a special starting winding in the stator, this winding being arranged so as to be highly inductive. The two windings are in parallel at first, and, the starting flux being entirely additional to the main flux, a powerful starting torque is obtained. Under running conditions the auxiliary stator winding is out of circuit and then represents so much idle copper.

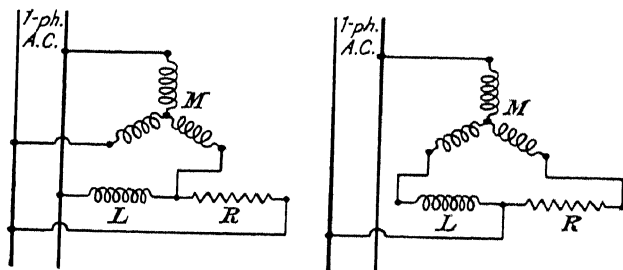


FIG. 364.—Typical monocyclic arrangements for starting induction motors on single-phase supply.

By the ordinary method of phase-splitting it is possible to obtain up to about $\frac{1}{4}$ full-load torque from a squirrel-cage (or about $\frac{1}{3}$ full-load torque from a slip-ring) single-phase motor, with twice full-load current. If it is permissible for the starting current to be 5 or 6 times the full-load value, about full-load torque can be developed at starting in small motors with a high-resistance starting winding.

Further information on phase-splitting motors is given in §§ 689-691.

(c) *Monocyclic Devices*.—Ordinary polyphase induction motors are used and the single-phase supply is converted to a polyphase system of E.M.F.'s by means of an inductance and ohmic resistance connected across the mains. Typical arrangements are shown in Fig. 364, the motor *M* being connected between the

mains and the common point of L and R ; or between one main and the outer terminals of L and R . (See also Fig. 285, § 689.)

Another method of running a standard 3-phase motor from a single-phase supply is shown in Fig. 365. Two terminals of a 3-phase 'pilot' motor are connected to the single-phase mains, and this machine is started by a monocyclic device (see above). Once the pilot motor is up to speed, there is available in its idle phase, C , an E.M.F. in quadrature with the single-phase supply E.M.F. If, therefore, the main motor be connected to the supply mains and the terminal C of the pilot motor, either directly or by star-delta switching, the main machine is self-starting.

The following data are quoted by G. Windred * concerning this, the Ferraris-Arno method of operation: Using a 5 H.P., 3-phase squirrel-cage machine as pilot motor, the starting torque of a 35 H.P. squirrel-cage motor with star delta switching was 26 % of full-load torque, the current taken from the mains being slightly greater than full-load current, and the current from the pilot motor being half this value.

This method is claimed to have given satisfactory results in traction and heavy crane service. The starting performance is better than that obtainable by the 'phase-splitting' system but inferior to that of a 3-phase motor on 3-phase supply. This fact and the fact that a pilot motor is required must be balanced against the simplicity of single-phase compared with 3-phase distribution.

An indirect method of starting a single-phase induction motor requires the provision of a special commutating winding on the rotor. The machine is started as a series or repulsion motor, with very high starting torque; and, when it reaches about half full-speed, a centrifugal device lifts the brushes and short-circuits the commutator, thus converting the rotor to a squirrel cage winding.

In principle, the speed of single-phase induction motors can be varied by the same methods as those employed for polyphase machines (§ 725). Apart from the I^2R losses involved, however, the use of rotor resistance to reduce the speed of a single-phase

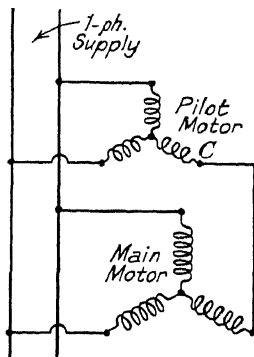


FIG. 365.—Single-phase operation of 3-phase induction motor by means of a pilot motor (stator circuits only shown).

* *El. Rev.*, Vol. 100, p. 874.

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induction motor is open to the objection that it reduces the maximum or pull-out torque of the machine. Also, the increase in starting torque, due to higher rotor resistance, is relatively low in single-phase induction motors and the torque at all speeds within the range of normal operation is much reduced.*

As noted in § 689, the pulsating field of a single-phase induction motor may be regarded as being the resultant of two fields rotating in opposite directions at equal speed, each field having a constant value equal to half the maximum value of the single-phase field. The torque due to one of these rotating fields is represented by the curve *a*, Fig. 366 (as in a 3-phase motor, see Fig. 276, § 681). The other rotating field produces a reverse torque represented by the continuation (*CD*) of the curve *a*. At standstill, the slip of the rotor is 100% with regard to both the component

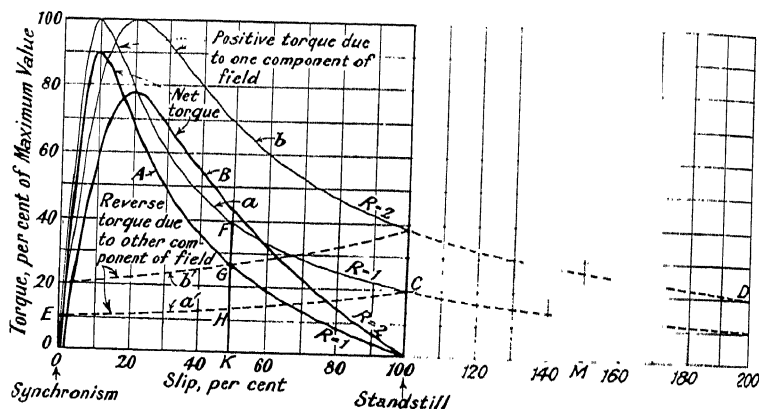


FIG. 366.—Torque-speed curves of single-phase induction motor.

rotating fields; the forward and reverse torques are therefore equal and opposite (represented by the point *C* in Fig. 366) and the net torque is zero. This shows that an induction motor with a single-phase field has no inherent starting torque; the component fields must be unbalanced before the motor will start.

When the motor is running at, say, half-synchronous speed the slip of the rotor is 50% with regard to the forward-rotating component of the field and the corresponding forward torque is represented by *KF*. At the same time, however, the rotor slip is 150% with regard to the backward-rotating component of the field, which therefore produces a reverse torque represented by *ML*. Subtracting *ML* from *KF*, we obtain the net torque *KG*.

If the curve *CD* be reversed into the position *CF*, the ordinate *KG*, equal to

* The effects of increased rotor resistance on the torque-speed characteristics may be seen by adding to the curves in Fig. 366 from Fig. 276. The particular curves in Fig. 366 relate to low values of rotor resistance. The effects of the latter are more pronounced at higher values.

the intercept HF , represents the net forward torque and, by repeating this construction, the curve A is derived from the forward and reverse torque curves a, a' .

Similarly, if the rotor resistance be doubled, the net torque curve B is derived from b, b' ; and so on. Comparison of the curves A, B , etc., shows the effect of increasing rotor resistance on the characteristics of the motor.

The inherent limitations of single-phase induction motors have been largely overcome by various means (§§ 689-692), and the applications of these machines are steadily increasing, particularly in the smaller sizes.

731. Starting and Controlling Synchronous-Asynchronous Motors.—Though the secondary circuits (usually on the rotor) of synchronous-asynchronous motors vary in different makes, all these machines are essentially slip-ring induction motors with phase-wound secondaries which are excited by D.C. when the motor is up to speed (§ 696). The motor is therefore started with resistance in the rotor circuit (§ 724) and develops, at full voltage, a starting torque equal to 2 to $2\frac{1}{2}$ times full-load torque with from $2\frac{1}{2}$ to 4 times full-load current. The external resistance in the rotor (secondary) circuit is removed progressively and the motor accelerates to its full induction speed (from 2 to 5 % below the synchronous speed). D.C. excitation is then applied to the secondary windings and the motor pulls into synchronism, against any torque up to about $1\frac{1}{2}$ times full-load torque. No speed-control is possible, except by pole-changing or by varying the supply frequency, but the P.F. of the motor and its pull-out torque may be varied by regulating the value of the D.C. field current. The motor will generally pull out of synchronism at about $1\frac{3}{4}$ times full-load torque if it is excited for 0.9 leading P.F. at full-load, and at twice full-load torque if it is excited for 0.8 leading P.F. The motor is usually designed so that it will run, at least temporarily, as an induction motor at loads exceeding the synchronous pull-out torque but not exceeding the stalling torque, which is equal to $2\frac{1}{2}$ to 3 times full-load torque.

The starting and running connections of a separately-excited synchronous-induction motor are shown in Fig. 293, § 696; and those of a self-excited (Fynn-Weichsel) motor are shown in Fig. 295, § 697, where also the distinctive starting characteristics of the latter type of motor are explained.

732. Control of Single-Phase Series Motors.—The single-phase series motor (§ 700) can be switched straight on to the mains where small fan motors or the like are concerned. Larger motors

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may be started by the application of reduced voltage using an auto-transformer,* as in Fig. 367. A limiting coil, L , is then used to avoid either breaking the circuit or short-circuiting turns of the auto-transformer when going from one contact to the next (see also § 396, Vol. 2). Fig. 368 shows diagrammatically the use of a double-wound transformer, T , with variable tapplings on the low-voltage side for starting and speed control, and a reversing switch R . Here again, limiting coils L are employed and the sequence of control is: close 1; close 2, open 1; close 3, open 2; and so on. If desired, an auxiliary switch can be used to short-circuit the coil L , in series with M , except when changing from one contact to another; this involves extra complication but it eliminates the loss which otherwise occurs in the coil L during normal running.

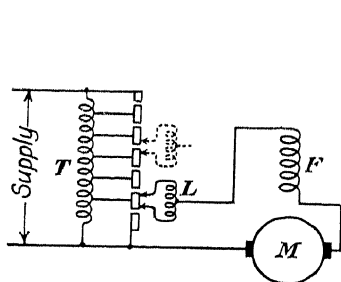


FIG. 367.—Starting single-phase series motor by auto-transformer.

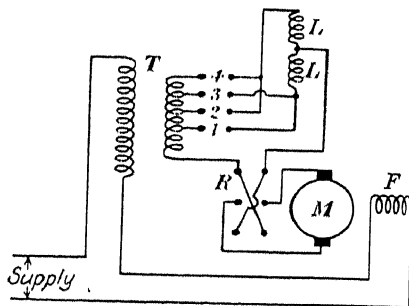


FIG. 368.—Control of single-phase series motor on high voltage supply.

The arrangement shown in Fig. 368 obviously provides only for step-by-step control of speed, but by placing an induction regulator (§ 406, Vol. 2) in series with M , this regulator having a range of $\pm v$ volts, continuous gradation can be obtained between transformer tapplings $2v$ volts apart.

The starting torque of the 1-phase series motor is high and the starting current relatively low, but the P.F. is low at starting.

If the motor is driven by an 'overtaking' load, *e.g.* a crane load being lowered, it can be operated as a generator to effect electro-dynamic braking.

* A series resistance might be used but the use of a transformer is much more economical, for it practically eliminates I^2R losses. Also, where high-voltage supply is concerned, a transformer is needed for normal running and is easily provided with tapplings for starting.

733. Control of Repulsion Motors.—The method of starting, reversing and controlling the speed of the simplest type of single-phase repulsion motor, by brush displacement from the neutral axis, is explained in § 701. Alternatively, the motor can be started by a graded series resistance (like a D.C. motor) or by an auto-transformer with suitable tappings, the motor brushes then being fixed in the normal running position. Reversal is then effected by reversing one of the stator windings in the Atkinson-type motor (Fig. 302, § 701); where a single stator winding is used (Fig. 303), the brush setting must be changed for reversal of rotation. Two stator windings of the type represented by Fig. 303 may be arranged symmetrically with regard to a fixed brush axis to provide for rotation in either direction; one of the

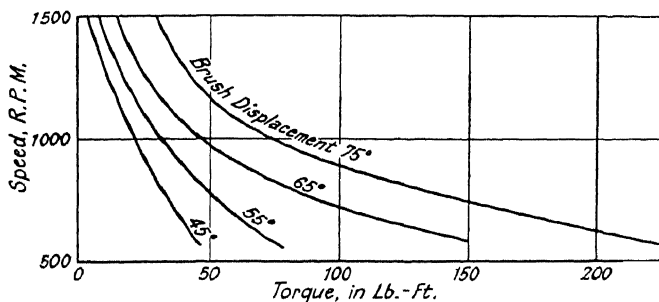


FIG. 369.—Torque-speed curves for single-phase repulsion motor with various values of brush displacement.

windings is used for forward and the other for reverse rotation, hence one is necessarily idle.

Typical curves showing the relation between torque and speed in a single-phase repulsion motor for various values of brush displacement are given in Fig. 369. Adjustment of speed by brush setting is easier in the Deri motor (§ 702) than in the ordinary repulsion motor with a single set of brushes.

Normally, speed control by brush shifting is only used in repulsion motors within a range from about 0.3 to 1.1 times synchronous speed. Where wider speed control or prolonged running at low speed is desired, the use of a variable tapping transformer should be considered.

Care should be taken that a repulsion motor is not left connected to the supply (except temporarily) with its brushes on

the neutral axis; under such conditions, the stator takes a heavy current at low-power factor, say 35 to 45 %, full-load current at 0.1 to 0.2 P.F.

734. Control of Single-Phase Shunt-Type Commutator Motor.—Machines of this type (§ 706) are usually started as repulsion motors. For example, with the connections shown in Fig. 370, the motor will start as a compensated repulsion motor (*cf.* Fig. 306, § 703). Subsequently, the brushes *EE* are connected through the resistance *R*, which is gradually short-circuited; the motor then operates as a shunt-type motor (*cf.* Fig. 314, § 706).

Speed control above and below synchronism may be obtained by means of a variable auto-transformer connected between the main brushes *BB*, Fig. 371. Alternatively, a variable-inductance

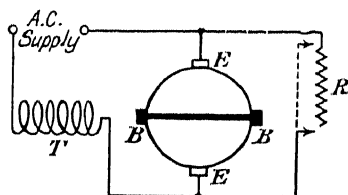


FIG. 370.—Single-phase shunt-type motor started as repulsion motor,

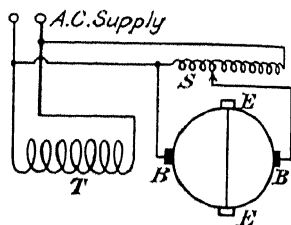


FIG. 371.—Speed control of single-phase shunt-type motor.

or a variable-tapping auxiliary coil on the stator may be connected between the brushes *EE*, the speed being lowered or raised according as the excitation is increased or decreased.

The starting and running connections of a Keighley Craft single-phase shunt-type two-speed motor as used for lift service are shown in Fig. 372.*

The connections for single-speed operation are shown diagrammatically at Fig. 372 (a); the connection *EE'* is closed after the machine has accelerated to synchronism. The speed can be raised above synchronism by injecting between *BB'* a small E.M.F. derived from a transformer which also supplies the quadrature component for P.F. correction. By reversing the injected E.M.F., the speed can be reduced below synchronism.

* From 'High Speed Lifts on Single-Phase Supply,' by R. E. Hopkins, *El. Rev.*, Vol. 104, p. 53.

In a certain case the motor for a two-speed 200/100 ft. per min., 15 cwt. lift was rated at 440 V, 40 \sim , 1 ph., 800 r.p.m. synchronous speed. The running speed was raised to 1 000 r.p.m. by the connections shown in Fig. 372 (b); and the speed was reduced to 500 r.p.m., for landing control, by reversing the injected E.M.F. as at (c), the brushes *E*, *E'* being connected to *B*, *B'* respectively in order to maintain correct compensation and a flat speed-load curve.

For reverse running, the starting connections are as at (a), but with the auxiliary winding reversed; the maximum-speed running connections are as at (b), but with the auxiliary winding and transformer primary reversed; and the half-speed connections are at (c), but with the auxiliary winding reversed, the transformer primary reversed, and the brushes *E*, *E'* connected to *B'*, *B* respectively.

The control board for reversible two-speed operation contains nine contactors. An interesting feature is that the heavy current between the brushes *BB'* is not handled by a contactor; the latter is in the primary circuit of the transformer where the current is only about one-tenth of that between the brushes.

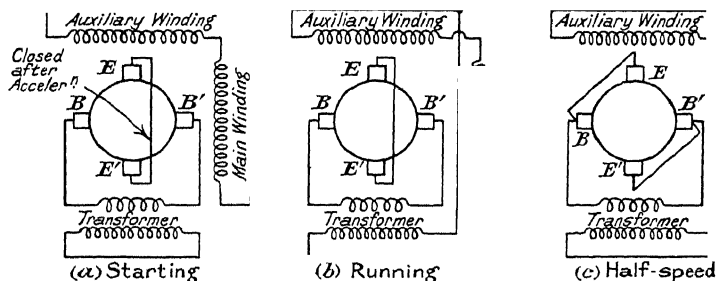


FIG. 372.—Two-speed single-phase shunt-type motor.

The efficiency of the particular machine mentioned in the preceding example was 84 % on full-load and the P.F. was 0.91. The starting consumption was 44 kVA when developing four-times full-load torque, equivalent to 60 H.P.

735. Control of Three-Phase Commutator Motors.—As explained in § 708 a three-phase *series-type* commutator motor can be started and controlled either by a variable-tapping transformer or by brush-shifting, the latter being the usual and more economical arrangement, besides giving a continuous gradation of speed. The motor has a definite series-type load-speed curve for each brush setting, and the actual range of speeds varies with the design of the motor and its rotor transformer, and with the torque characteristics of the load. At constant full-load torque, the speed range is usually about 3:1 but, taking into account the series characteristic of the machine, the motor may run at any speed

from zero up to about $1\frac{1}{2}$ times synchronous speed on loads of variable torque. Reversal is effected by moving the brushes to the other side of the short-circuit axis. For good commutation the rotor and the rotating field of the stator should run in the same direction. The brush displacement from neutral is then in the opposite direction to the rotor rotation.

Where the torque of the load decreases rapidly with speed, as in the case of a centrifugal fan or pump, it is recommended that the stator connections be changed from delta to star at, say, two-thirds of full-load speed, thus maintaining higher P.F. and efficiency at the lower speeds than would result if the speed were reduced by brush displacement alone.

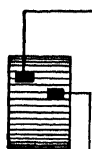


FIG. 373.—Series-parallel switching of stator windings for increasing speed range of 3-ph. commutator motor.

In the case of a 3-phase *shunt-type* commutator motor (§ 709), speed control is obtained by varying the E.M.F. applied to the secondary. If the latter is on the rotor then, with an applied E.M.F. equal and opposite to that induced by the stator, the machine remains stationary. On reducing the applied voltage the motor starts, and runs at higher speeds as the applied voltage is decreased until, when the applied voltage is zero, the

motor runs at synchronous speed (less slip). Speeds above synchronism are obtained by reversing the applied voltage, so that it aids the induced E.M.F. When the machine is running below synchronism the energy of slip is returned to the mains, the requisite conversion of frequency being effected by the commutator. On the other hand, when the machine is running above synchronism supplementary energy is drawn from the mains to provide the energy of 'negative' or 'overtaking' slip. Though the range of speed control is generally restricted to 3 : 1, or to 5 : 1 in specially wound machines, it is possible to obtain up to 10 : 1 speed range without rheostatic control by arranging for series-parallel switching of the stator windings, as shown in Fig. 373, which represents one phase only of the stator windings in a rotor-fed motor of the type shown in Fig. 323, § 709.

The simplicity of the rotor-fed, 3-phase shunt motor is an

important advantage. The machine is started, stopped and regulated in speed over a range of 3 or 4 to 1 by means of a brush-shifting lever or hand-wheel; this, and a 3-pole switch and fuses, are the only apparatus required for control and protection. Comparatively little extra equipment is needed to provide for inching speeds and a wider range of continuous regulation.

736. Definitions of Types of Motor Starters, Controllers, and Field Rheostats.—The following definitions are substantially those given in the British Standard Specifications cited in the bibliography, § 745; but the Specifications themselves should be consulted when the actual text is required.

Motor Starter.—A device arranged for starting and accelerating a motor to normal speed, but having no running position other than 'full on.' The term includes: rheostatic starters; auto-transformer starters; and switch starters.

Rheostatic Starter.—A resistance and a means for readily varying its amount. The term includes: face plate starters; drum starters; multiple switch starters; contactor starters; and liquid starters.

Auto-Transformer (or Compensator) Starter (for 2- and 3-phase A.C. motors).—An auto-transformer and switch are so arranged that, when the switch is on the starting contact(s), a reduced voltage is applied to the motor.

Switch Starter (for induction motors).—Switches provide for different couplings of the stator windings when in the starting and running positions respectively. A *series-parallel switch starter* for a 2-phase induction motor connects all the stator windings of each phase in series for starting and in two equal circuits in parallel for running. A *star-delta switch starter* for a 3-phase induction motor connects the stator windings in star for starting and in delta or mesh for running.

Controller.—A device having several steps, contacts or positions (sometimes called notches), used with or without resistances to regulate the speed of a motor or motors. It may or may not be used for starting. The term 'controller' does not include the resistances or other means of control employed therewith. Simple *shunt regulators* are not included in this definition.

Face Plate Starter (or Controller).—The contact parts are arranged on a plane surface.

Drum Starter (or Controller).—The moving contact parts are arranged on a cylindrical surface.

Multiple Switch Starter.—Each contact consists of a separate hand-operated switch.

Multiple Switch Controller.—Separate hand-operated switches or circuit breakers are arranged to operate in a definite order to insert resistances or change connections to vary the speed of the motor.

Change-Over Switch Controller.—A multi-contact switch is arranged to vary the circuit connections by the movement of one or more common blades or moving contacts.

Contactor Starter (or Controller).—The contacts for the main current are made by *contactors*, i.e. switches operated electromagnetically or electropneumatically and suitable for frequently opening and closing the circuit.

Master (or Pilot) Controller.—A multi-way switch controlling the operation of a set of contactors.

Master Switch.—A single-way switch which may be used to control the operation of a contactor or set of contactors.

Limit Switch.—A switch for preventing over-travel, arranged to be mechanically operated by the motion of the machine driven.

Liquid Starter.—A rheostatic starter employing a liquid resistance material.

Enclosure of Starters, Resistances, Etc.—The B.S. Specifications cited above define forms of enclosure as follows: open, enclosed ventilated, drip-proof, weather-proof (splash-proof), totally enclosed, oil-immersed, and flameproof (including explosion-proof). These definitions are consistent with those for motor enclosures, § 670.

Rheostat.—A resistor provided with means for readily varying the amount of resistance in circuit.

Field Rheostat.—A rheostat for varying, at will, the current in the field winding of a machine.

Shunt-Field Rheostat.—A field rheostat suitable for connection in series with the shunt winding of a machine.

Potentiometer-Type Field Rheostat.—A field rheostat in which the resistor is suitable for connection across the source of supply, means being provided for connecting the field winding between various points on the resistor to vary the P.D. applied to the field winding. Part of the resistor is then in parallel with the field winding and part in series therewith.

Reversible Potentiometer-Type Field Rheostat.—A potentiometer-type field rheostat arranged for reversing the polarity of a field winding.

Field-Divertor Rheostat.—A rheostat suitable for connection in parallel with a field winding.

Balancer-Field Rheostat.—The resistor is permanently connected between the neutral terminals of the shunt-field windings of a balancer, and means are provided whereby the neutral can be connected to various points of the resistor.

Interlocked Field Rheostat.—Means are provided for ensuring full field strength when starting the motor.

737. Rating of Starters, Controllers, and Rheostats.—The principal factors which enter into the rating of any apparatus for the control of motors are the voltage of the circuit in which the apparatus is to be used; the length of time for which the apparatus is in circuit; the frequency of recurrence of this period; the current to be handled during the period of service; and the temperature rise permissible in the various parts of the apparatus. British standard ratings based on these factors are specified in the B.S.I. publications cited in the bibliography, § 745; they vary considerably with the type of starter or controller concerned and the full specification for each should be studied. It is important to realise that any electric motor and its control gear are complementary, each to the other. Unless the type and rating of the starter and controller are adapted to the motor and the requirements of the driven load, the best possible results cannot be obtained from the motor. The manufacturer of motor control gear must be given full par-

ticulars of the motor, the driven machine, and any restrictions which may be imposed by the supply authority (*e.g.* maximum starting current, current increment, etc.), otherwise satisfaction cannot be guaranteed. Loads having a heavy 'flywheel effect,' *i.e.* high inertia, such as heavy lineshafts, punching and other machines with flywheels, absorb much energy during the period of acceleration; the duration of the starting period is consequently prolonged and the starting resistances must, therefore, be designed more liberally in order to avoid excessive heating.* The bases of design for different types and sizes of starters and controllers are given in the B.S. Specifications mentioned above.

738. Constructional Features of Motor Control Gear.—

There is an almost infinite variety of gear available for the control of D.C. and A.C. motors including starting straight-on or by regulated steps, with or without subsequent speed variation, with or without provision for reversal or dynamic braking, and so on. It is one of the great advantages of electric driving that almost any control requirements can be met by hand-operated or automatic gear, and this fact in itself makes it impossible here to describe all the combinations of methods and apparatus employed. In order, however, to indicate the principal features of the main types of motor control gear as made by a particular firm, the following notes have been prepared from information kindly supplied by Messrs. Brookhirst Switchgear Ltd. (Chester). The designs of different manufacturers vary considerably in details, but the range of gear described below is thoroughly representative of first-class practice. For convenience of reference, the notes are arranged under the following headings:—

D.C. GEAR.

- I (a) Faceplate starters : hand operated.
- (b) Drum-type inching starters : hand operated.
- (c) Multiple lever inching starters : hand operated.
- (d) Automatic control gear : solenoid and contactor types.

A.C. GEAR.

- II (a) Straight-on starters : 'contactor-break' ; hand operated.
- (b) Straight-on starters : oil immersed ; hand operated.
- (c) Straight-on starters : contactor type ; automatic.

* Valuable data concerning the friction torque and stored energy of various classes of machinery, together with a full consideration of the influence of these and allied factors on the design of motor starters are to be found in 'Electric Motor Starters,' J. Anderson, *Jour. I.E.E.*, Vol. 60, p. 619.

- III (a) Star-delta starters : 'contactor-break' ; hand operated.
- (b) Star-delta starters : oil immersed ; hand operated.
- (c) Star-delta starters : automatic contactor type.
- IV (a) Auto-transformer starters : oil immersed ; hand operated.
- (b) Auto-transformer starters : automatic contactor type.
- V (a) Stator-rotor starters : 'contactor-break' ; hand operated.
- (b) Stator-rotor starters : oil immersed ; hand operated.
- (c) Stator rotor starters : automatic contactor type.
- VI Synchronous motor starters : oil immersed ; hand operated.

The introductory general notes below are followed by specific notes on typical starters in each of the groups I to VI.

GENERAL.—All the starters described are enclosed in iron cases, usually for wall-mounting only in the smaller sizes and for either wall or pedestal mounting in the larger sizes. Usually, the door of the case is so interlocked that it cannot be opened while the switch-gear is live. In the case of D.C. and air-break A.C. apparatus, the gear cannot be made live while the door is open, but it should be noted that oil-immersed gear can generally be made live by closing the isolating switch after the tank has been lowered, though the isolator must be opened before the tank can be lowered ; where this is possible, precautions should be taken, *e.g.* the isolating switch might be padlocked 'off.' Normally, the cases are ventilated but the ventilating openings are protected by drip-proof hoods ; if desired, the casing can be made dustproof. Windows are commonly provided in the cases of air-break control gear, and they may be protected by wire guards. Provision is always made for mounting an ammeter on the casing, but this is usually an 'extra.'

In no case can starters be left in an intermediate position ; unless the starting operation is completed the gear returns automatically to 'off,' or a fresh start is made necessary.

Protection of D.C. motors is usually secured in the case of the smaller machines (up to about 10 H.P.) by no-volt and overload releases and fuses, and in the case of larger machines by a circuit breaker with no-volt and overload releases. Where speed regulation of D.C. machines is provided, the shunt field regulator is interlocked with the starter so that the motor cannot be started without full excitation.

In 3-phase gear two overload trips are sufficient unless the supply has an earthed neutral ; three trips are then required. If there are likely to be peak loads during normal running, the overload trips should be fitted with time lags, or have inherent time-

delay action, as in the case of thermal type overload trips. A hand-resetting device is usual on the overload trips of automatic gear to prevent the contactor from 'pumping' when 'on' and 'off' control (other than push buttons) is employed. Automatic solenoid- or contactor-type starters provide for control by start and stop push-buttons; by start, inch and stop push buttons; or by float, diaphragm or other automatic or manual master switch.

I (a) D.C. FACEPLATE STARTERS: HAND OPERATED.

The simplest type of *non-inching faceplate starter* is designed for use with *separate switches and fuses*. The starter can then contain only the starting resistance, the plain lever starting handle moving over a series of renewable copper contacts on the faceplate, a no-volt release (and if required) an overload trip which operates by opening the no-volt release circuit. The starting lever is returned automatically by a spring when the no-volt release operates. The lever carries a laminated brush contact in the larger sizes and a spring-controlled copper slipper contact in the smaller sizes. Final contacts, independent of the starting contacts, are fitted if required. A carbon roller wiper is fitted to the first contact only in small sizes, and to all contacts in larger sizes, to protect the copper contacts against damage by arcing. Press-button release is provided. Standard sizes range from $\frac{1}{2}$ to 30 H.P. at 100 to 125 V; $\frac{1}{2}$ to 50 H.P. at 200 to 250 V; and $\frac{1}{2}$ to 60 H.P. at 400 to 550 V.

The simple type of faceplate starter described in the preceding paragraph has few, if any, applications except where suitable main switches and fuses are already installed. In other cases it is obviously advantageous to purchase a self-contained control unit with all the control gear in a single casing.

A *non-inching faceplate starter* of this type, *complete with main switch and fuses* is shown in Fig. 374.* At the top of the panel is a faceplate starter with no-volt release. Below this is a shunt regulator, which is mechanically interlocked so that the starter arm cannot be moved unless the shunt regulator is in the 'full-field' position. Usually, this regulator provides for speed variation up to 50 % above normal, but standard designs are available for speed variation up to three times normal, and yet wider ranges can be provided if required. If no speed control is required, the shunt regulator is omitted. Below the shunt regulator are two fuses with an overload trip between them; the latter operates by opening the no-volt release circuit. Finally, in a separate compartment at the bottom of the case there is a quick-break main switch which serves also as an isolator. The outer door can only be opened when the main switch is 'off,' and the latter cannot be closed until the inner and outer doors have been shut. Terminals are provided for a remote push-button release circuit. Standard sizes range from $\frac{1}{2}$ to 5 H.P. at 100 to 125 V; 1 to 10 H.P. at 200 to 250 V; and 1 to 12 H.P. at 400 to 550 V.

I (b) D.C. DRUM-TYPE 'INCHING' STARTERS: HAND OPERATED.

The special feature of the control gear shown in Fig. 375 is the special ratchet handle on the starter drum. Swinging this handle through 180 degrees in a vertical

*The illustrations, Figs. 374-382 inclusive, show typical control gear made by Messrs. Brookhirst Switchgear, Ltd., Chester, and are from blocks kindly supplied by that firm.

plane through the axis of the drum closes a control switch at the other end of the latter. This control switch is in the circuit of the main contactor and, once it has been closed, the drum can be notched forward by means of the ratchet handle until the 'full on' position is reached. If the ratchet handle be released in any intermediate position, the control switch opens the main contactor, and the latter cannot be closed again until the drum has been returned to 'off.' The drum cannot inadvertently be ratcheted past the 'full on' position, but it can be returned to 'off' by a single movement of the handle when desired, without ratcheting back through the starting positions. The main current is always broken by the double-pole contactor with magnetic blow-outs, whether the interruption is caused by the control switch on the drum starter, by overload, by failure of supply, or by opening of the isolating switch.

Referring to Fig. 375, the shunt regulator at the top of the panel is worm driven and interlocked so that full-field must be established before the motor can be started. Below this there are, in order, the drum starter, two overload trips, the isolator handle (interlocked with the doors), the main contactors (which serve also as no-volt protection), and the isolating switch, which is of the slow-break type as the circuit is always broken by the contactors. From 50 to 300 % speed variation, as required, is provided by the shunt-regulator; and, if no speed variation is desired, the shunt-regulator is omitted. 'Inching' is effected by the ratchet handle operating the control switch, or by push-buttons; in both cases the full starting resistance is in circuit and links are provided so that the ohmic value of the starting resistance, and therefore the degree of 'inching,' can be varied.

Standard sizes of this control gear range from $\frac{1}{2}$ to 50 H.P. at 100 to 125 V; $\frac{1}{2}$ to 100 H.P. at 200 to 250 V; and $\frac{1}{2}$ to 175 H.P. at 400 to 550 V.

I (c) D.C. MULTIPLE-LEVER 'INCHING' STARTERS: HAND OPERATED.

In this equipment, the sections of starting resistance are cut out by a series of lever switches, actuated by cams on a spindle rotated by a ratchet handle. The cam spindle, in fact, performs through the lever switches exactly the same function as the contact drum of the drum-type starter described at I (b) above. The remaining components are essentially the same as in the drum-type gear. The shunt-regulator provides from 30 to 100 % speed variation as required. The multiple-lever type of starter is specially suitable for high-power motors. Standard sizes range from 50 to 150 H.P. at 100 to 125 V; 70 to 500 H.P. at 200 to 250 V; and 80 to 750 H.P. at 400 to 550 V.

I (d) D.C. AUTOMATIC CONTROL GEAR.

Representative examples of automatic control gear for D.C. motors are illustrated in Figs. 376 to 378, viz. a non-inching contactor type starter (Fig. 376) suitable for motors up to about 5 H.P.; a solenoid-operated inching starter (Fig. 377) suitable for motors up to about 60 H.P.; and a contactor-type inching starter (Fig. 378) suitable for motors up to about 500 H.P. In each case, the gear is shown with a shunt-regulator for speed variation, but this can be omitted if no speed control is desired. A distinctive feature of the solenoid-operated panels illustrated is the wedge-type contact bar of the automatic starter. In this, successive spring-controlled carbon blocks (resembling the brushes of a motor) are short-circuited in proper sequence by the wedge-shaped bar lifted by the operating solenoid. Full-face contact is made between the bar and the brushes on each step. In the smaller equipments (Fig. 377), the carbon brushes are connected to the sections of starting resistance, but on the larger panel (Fig. 378) the solenoid starter acts only as



FIG. 374.—Non-inching face-plate starter for D.C. motors, with main switch, fuses and shunt-regulator for speed variation.

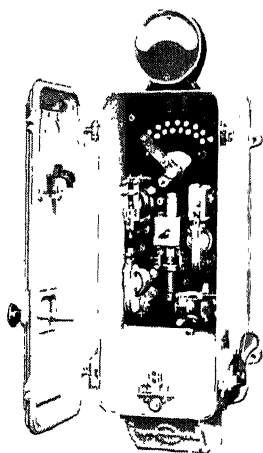


FIG. 376.—Automatic contactor-type starter for small D.C. motors. Non-inching; variable speed.

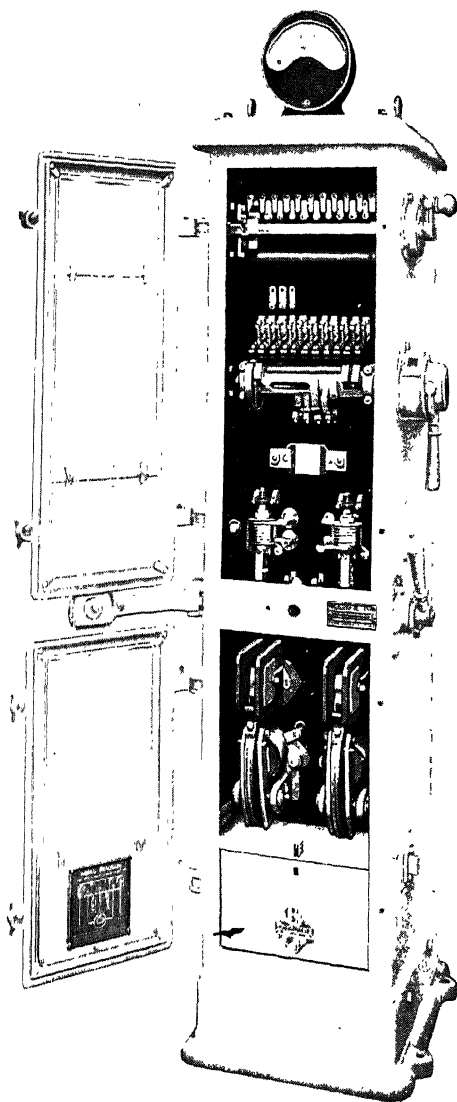


FIG. 375.—Inching drum-type starter for D.C. motors, with contactors, overload trips and shunt-regulator.

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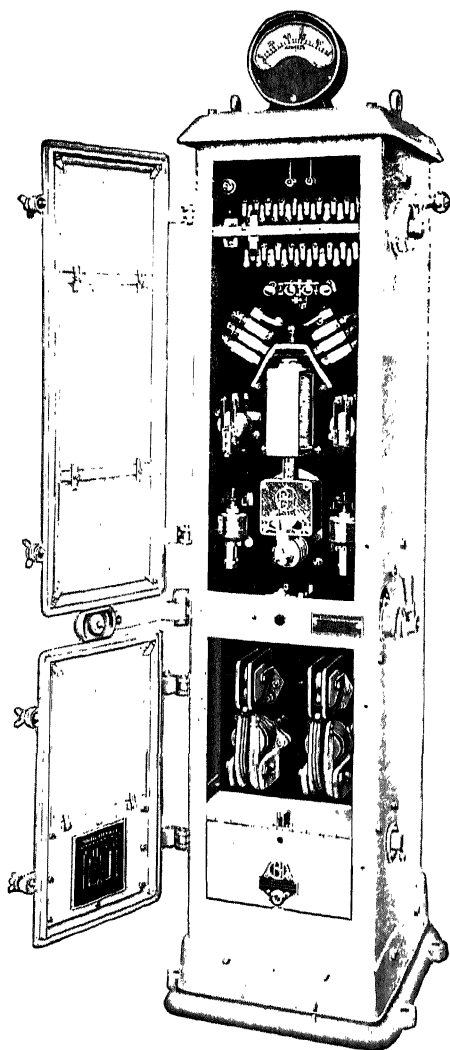


FIG. 377.—Automatic solenoid-type starter for D.C. motors. Inching; variable speed; hand regulator.

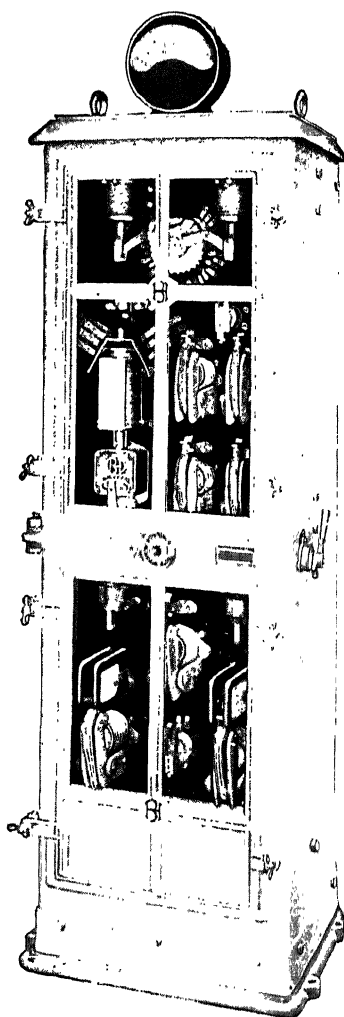


FIG. 378. Automatic contactor-type starter for D.C. motors. Inching; variable speed; auto-regulator.

[To face page 251.]

a master controller, the brushes being connected to contactors which cut out the resistance sections.

A suitable rate of starting is secured in the smallest starter (Fig. 376) by means of an air dashpot retarder. The larger starters are controlled by eddy current retarders, which are not adversely affected by changes in temperature. The core of the starter solenoid acts through gearing to rotate an aluminium disc, which runs between the poles of an electromagnet excited by the main current of the motors. The braking effect exerted by the disc thus increases with the load on the motor, and the rate of starting is automatically reduced; at the same time, there is no risk of the solenoid core being held stationary at any intermediate position (leaving part of the starting resistance in circuit) because the eddy current braking becomes weaker as the speed of the solenoid core and, therefore, the aluminium disc, decreases. A one-way clutch allows the solenoid core to fall freely to 'off,' without retardation by the eddy current brake.

In all sizes of starting panels 50 % speed variation is standard, but 200 to 300 % can be provided if necessary. In all cases it is essential that the shunt-regulator resistance be cut out of the field circuit during the starting period. This is effected by an automatic accelerating relay which short-circuits the regulating resistance during the starting operation, and thereafter re-inserts it gradually into the field circuit, so that the motor accelerates automatically to the speed for which the shunt-regulator is 'set.' If the 'set' speed has only to be changed occasionally, the shunt-regulator may be adjusted by a handle and worm gear (Fig. 377), but if frequent changes are required it is convenient to use a solenoid-operated regulator (Fig. 378). This comprises 'accelerate' and 'retard' solenoids, controlled by push-buttons from any convenient position, the solenoid cores moving the regulator arm in one direction or the other, step by step through a ratchet mechanism.

The equipment of the small *contactor type starter with hand regulator* in Fig. 376 includes a double-pole, slow-break isolating switch, in an inner compartment, interlocked with the contactor starter and the door of the case; automatic accelerator; a hand-operated radial-pattern shunt-regulator (50 % speed variation); a contactor type starter with air dashpot retarder, and a magnetic blow-out on the first contactor. Standard sizes range from $\frac{1}{2}$ to $2\frac{1}{2}$ H.P. at 100 to 125 V; and 1 to 5 H.P. at 200 to 250 V or 400 to 550 V.

The *inching solenoid-type starter with hand regulator* in Fig. 377 includes (going downwards from the top) a hand-operated shunt-regulator, normally for 50 % speed variation but up to 300 % variation can be provided; a solenoid-operated wedge-type contact starter with eddy current retarder, but no magnetic blow-out, the circuit being always broken by the contactors; automatic accelerator restoring full field during the starting period and then accelerating the motor to the set speed; overload trips (on each side of the eddy current retarder); an isolator handle interlocked with the doors; two magnetic blow-out contactors, one in each pole; and a slow-break isolating switch in the bottom compartment. The contactors provide no-volt protection, and are interlocked so that they cannot close unless the starter is 'off.' The isolating switch is interlocked with the doors and with the contactors so that the latter always make and break the current. Standard sizes range from $\frac{1}{2}$ to 15 H.P. at 100 to 125 V; $\frac{1}{2}$ to 35 H.P. at 200 to 250 V; and $\frac{1}{2}$ to 60 H.P. at 400 to 550 V.

The *inching contactor-type starter with auto-regulator* shown in Fig. 378 comprises (from the top downwards) a solenoid-operated ratchet type shunt-regulator, giving 50 % speed variation (up to 300 % if desired); a solenoid-operated wedge-type master switch and (to the right of the latter) an automatic accelerator and

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four starting contactors actuated by the wedge-type master-switch; an interlocked isolator handle; two overload trips; two main contactors and (between them) the fifth starting contactor and inching relay; and (at the bottom) a double-pole slow-break isolating switch. The main current is made and broken on the main contactors; interlocking is as explained in the preceding paragraph. Standard sizes of this gear range from 11 to 125 H.P. at 100 to 125 V; 25 to 225 H.P. at 200 to 250 V; and 40 to 500 H.P. at 400 to 550 V.

II (a) A.C. STRAIGHT-ON STARTERS WITH THERMAL OVERLOAD TRIPS AND FAULT PROTECTION FUSES: 'CONTACTOR-BREAK'; HAND OPERATED.

The equipment consists of a 3-pole electrically operated contactor; no-volt feature inherent; and two thermal type overload trips; also 3-pole cartridge fuses of high rupturing capacity giving protection under modern conditions. The fuses are arranged to open circuit independently of the starter. Replacement of fuses is limited to fault conditions; replacements are, therefore, infrequent. Three spare fuse cartridges are fixed inside the front door of the starter enclosing case. A triple-pole isolator, interlocked with the contactor, fitted in a separate locked compartment gives protection against contact with live parts. Standard sizes of this type of starter range from $\frac{1}{2}$ to 90 H.P. at 200 to 250 V; $\frac{1}{2}$ to 150 H.P. at 400 to 480 V; and $\frac{1}{2}$ to 175 H.P. at 500 to 550 V.

II (b) A.C. STRAIGHT-ON STARTERS: OIL IMMERSIBLE: HAND-OPERATED TYPE.

A 3-pole circuit breaker and combined starting switch fitted with rolling butt contacts are operated by a crank handle. The starter is arranged to connect the motor direct to the line in the starting position, and to connect the overload trips in circuit when the starter is pulled over into the running position. The starter when open completely isolates the motor. Time lags, fitted to the overload trips, prevent the starter from being tripped, by momentary overloads and normal starting peaks, but function in the event of sustained overload. A no-volt release mechanism releases the starter which returns automatically to 'off' position, and the starter may be tripped by an emergency stop push-button fitted to the case. A third overload trip is added for systems with earthed neutral, and a 3-pole isolating switch may be fitted if desired. When fitted, the isolator is interlocked to prevent the top cover and the oil tank being removed unless the supply is cut 'off.' Standard sizes range from $\frac{1}{2}$ to 35 H.P. at 200 to 250 V; $\frac{1}{2}$ to 75 H.P. at 400 to 480 V; and $\frac{1}{2}$ to 90 H.P. at 500 to 550 V.

II (c) A.C. STRAIGHT-ON STARTERS: AUTOMATIC CONTACTOR TYPE.

A 3-pole contactor connects the motor straight across the mains when the 'start' push-button or master switch is operated; and disconnects the machine when the 'stop' button or master switch is operated, or when the isolating switch is opened (if the latter be provided). The contactor has butt contacts, and two overload trips of the thermal type are arranged to open the contactor on sustained overloads, but not on momentary overloads during running, nor on normal starting peaks. Three cartridge fuses provide short-circuit protection under modern conditions. The contactor coil itself provides no-volt release. A triple-pole isolator in separate locked compartment protects against accidental contact. Standard sizes range from $\frac{1}{2}$ to 75 H.P. at 200 to 250 V; $\frac{1}{2}$ to 150 H.P. at 400 to 550 V.

III (a) A.C. STAR DELTA STARTERS: 'CONTACTOR-BREAK'; HAND OPERATED. WITH THERMAL OVERLOAD TRIPS AND FAULT PROTECTION FUSES (Fig. 379).

The equipment consists of an electrically operated T.P. main contactor with butt contacts; no-volt feature inherent. Star-delta starter 'inching,' fitted with

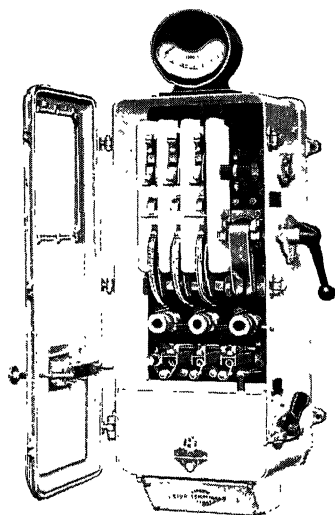


FIG. 379.—Hand-operated 'contactor-break' star-delta starting panel with thermal overload trips and fault protection fuses ; no-volt feature inherent.

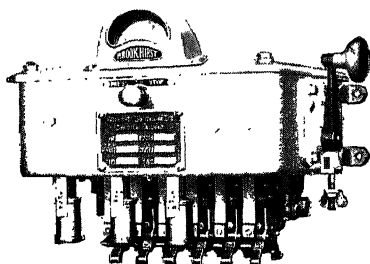


FIG. 380.—Oil-immersed star-delta starter with no-volt and two overload trips and time lags ; oil tank removed.

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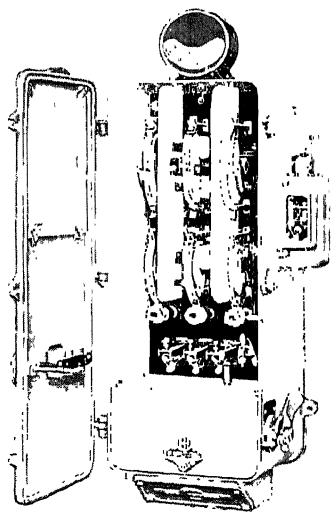


FIG. 381.—Star-delta starter ; auto-
matic contactor type.

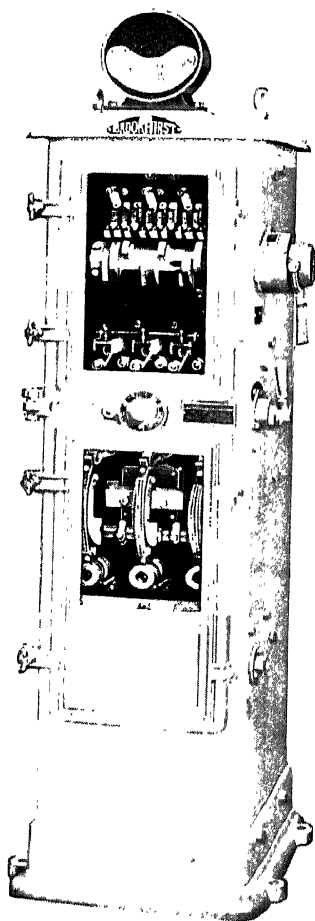


FIG. 382. Hand-operated 'contactor-
break' stator-rotor starting panel with
thermal overload trips and fault protection
fuses ; no-volt feature inherent.

[To face page 253.

butt contacts and normally connected so that on pressing the start-inch push-button, the main contactor closes to start the motor. After an interval to allow the motor to accelerate the starter is pulled over into the running position, when the start-inch push-button may be released. The panel is fitted with two thermal overload trips and three fault protection fuses which function as described under II (a). Standard sizes range from $\frac{1}{2}$ to 90 H.P. at 200 to 250 V; $\frac{1}{2}$ to 175 H.P. at 400 to 480 V; and $\frac{1}{2}$ to 200 H.P. at 500 to 550 V.

III (b) A.C. STAR-DELTA STARTERS: OIL IMMERSSED; HAND-OPERATED TYPE.

The star-delta starter, fitted with rolling butt contacts (Fig. 380), is operated by a crank handle, and arranged to make the connections in star, in the starting position. After an interval of time to allow the motor to accelerate, the starter is pulled over into the running position, connecting the overload trips in circuit. The starter when open completely isolates the motor. The overload trips are fitted with adjustable time lags and a no-volt mechanism operates as described under II (b). A single point stop push-button is fitted which trips the starter to stop the motor. A third overload trip is added for systems with earthed neutral, and a 3-pole isolating switch may be fitted if desired, at extra cost. These features are arranged as previously described under II (b). Standard sizes range from $\frac{1}{2}$ to 45 H.P. at 200 to 250 V; $\frac{1}{2}$ to 90 H.P. at 400 to 480 V; and $\frac{1}{2}$ to 100 H.P. at 500 to 550 V.

III (c) A.C. STAR-DELTA STARTERS: AUTOMATIC CONTACTOR TYPE.

This panel (see Fig. 381) is provided with an electrically operated T.P. main contactor; no-volt feature inherent, and change-over contactors for star and delta connections. The latter are interlocked so that both cannot close simultaneously, and they are actuated by a solenoid-operated relay with air dashpot timing device giving an adjustable time interval, between the closing of the 'start' (star) and 'run' (delta) contactors. Two thermal type overload trips are provided, and three cartridge fuses give short-circuit protection under modern conditions as described under II (c) above. A triple-pole isolating switch is interlocked with the doors of the casing so that the latter cannot be opened until the isolator is 'off,' and the isolator cannot be closed until the doors are shut. Further, the isolator is interlocked with the contactor so that the circuit is always completed and broken by the latter. In other words, the isolator is used solely as an isolating switch and never breaks current; it is therefore of the slow-break type. Standard sizes of this controlgear range from $\frac{1}{2}$ to 80 H.P. at 200 to 250 V; $\frac{1}{2}$ to 175 H.P. at 400 to 550 V.

IV (a) A.C. AUTO-TRANSFORMER STARTERS: OIL IMMERSSED; HAND-OPERATED TYPE.

The particulars given for star-delta starters at III (b) above apply also to the auto-transformer type, except that the starting switch now connects the motor to auto-transformer and full voltage instead of in star and delta. The oil-immersed auto-transformer has tapplings for 40 %, 60 %, and 75 % of line voltage. Standard sizes range from $\frac{1}{2}$ to 45 H.P. at 200 to 250 V; $\frac{1}{2}$ to 90 H.P. at 400 to 480 V; and $\frac{1}{2}$ to 100 H.P. at 500 to 550 V.

IV (b) A.C. AUTO-TRANSFORMER STARTERS: AUTOMATIC CONTACTOR-TYPE.

The switchgear, interlocking and overload protection in this equipment are essentially the same as in the automatic contactor-type star-delta starter (see III (c) above), but the function of the contactors is now to connect the motor successively to the reduced voltage provided by the auto-transformer and then to the full supply

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voltage. The contactors are interlocked to prevent simultaneous closing; and actuated by a solenoid-operated master relay with adjustable timing device as before. The air-cooled auto-transformer is mounted in the same case as the switchgear and provided with three tappings so that the motor can be started on 40 %, 60 %, or 75 % of line voltage as desired. Standard sizes range from $\frac{1}{2}$ to 90 H.P. at 200 to 250 V; $\frac{1}{2}$ to 175 H.P. at 400 to 550 V.

V (a) STATOR-ROTOR STARTERS: 'CONTACTOR-BREAK'; HAND OPERATED.

A rotor starter of the drum type 'inching' (see Fig. 382) is operated by a ratchet lever handle and interlocked with the 3-pole stator contactor so that the motor cannot be switched on unless the full rotor resistance is in circuit. Overload protection is provided by two thermal type overload trips, and three cartridge fuses protect against modern short-circuit conditions. The slow-break isolator is enclosed in a separate compartment, and interlocked with the main door so that the latter cannot be opened unless the isolator is 'off'; also the isolator cannot be closed while the door is opened. T.P. stator contactor provides no-volt release and a stop-push-button is provided. Standard sizes provide for maximum rotor currents from 50 to 250 A, covering 1 to 90 H.P. at 200 to 250 V; 1 to 175 H.P. at 400 to 480 V; and 1 to 200 H.P. at 500 to 550 V.

V (b) A.C. STATOR-ROTOR AND STARTERS: OIL IMMERSIBLE; HAND OPERATED TYPE.

The stator contacts (of the butt type) and the rotor starting resistance are oil immersed. The resistances are cut out of circuit step by step, giving slow motion starting, by a ratchet handle actuating the drum type starter. Once commenced, the starting operation must be completed in correct sequence, otherwise the starter is tripped and the operator must begin again. The starter is provided with no-volt release and two overload trips of the solenoid type with adjustable time lags are fitted in front and enclosed within a separate accessible cover. The same remarks apply concerning isolating switch as in the oil-immersed straight-on hand-operated starter (see II (b) above). Standard sizes provide for rotor currents from 50 to 150 A, corresponding to from $\frac{1}{2}$ to 45 H.P. at 200 to 250 V; $\frac{1}{2}$ to 90 H.P. at 400 to 500 V; and $\frac{1}{2}$ to 90 H.P. at 500 to 550 V.

V (c) A.C. ROTOR STARTERS: AUTOMATIC CONTACTOR TYPE.

The starting resistance is star-connected, air-cooled and mounted in the control pillar casing. A 3-pole stator contactor with magnetic blow-outs, no-volt feature inherent, is interlocked so that it can only be closed when all the rotor resistance is in circuit. Thereafter, a series of double-pole electromagnetic contactors cut out the rotor resistance step by step. Each contactor is controlled by an adjustable automatic timing device of the air dashpot type. Two thermal type overload trips operate on the stator contactor. The main circuit is always made and broken by the latter, hence the isolating switch is of the slow-break type. Three cartridge fuses are provided which protect against modern short-circuit conditions. Standard sizes deal with maximum rotor currents from 35 to 250 A, corresponding to $\frac{1}{2}$ to 80 H.P. at 200 to 250 V; $\frac{1}{2}$ to 175 H.P. at 400 to 550 V.

VI A.C. SYNCHRONOUS MOTOR STARTERS:] OIL IMMERSIBLE; HAND-OPERATED; MULTIPLE SWITCH TYPE.

The starter is actuated by a ratchet handle ensuring step by step motion, and unless the starting operation is completed in correct sequence the circuit breaker is tripped and cannot be re-closed without returning to off. An air-cooled, cast-iron grid starting resistance is provided, and normally rated for three successive 1-min.

starts against full-load torque. The 3-pole circuit breaker is in the same oil tank as the starter and operated by the same ratchet handle. The motor can be 'inched' by raising the handle, making one forward movement and releasing the handle. A no-volt release and press-button trips are provided; also three overload trips fitted with time-lags and effective in any position of the handle. A slow-break isolating switch is interlocked with the doors, tank lowering gear, and circuit breaker. An exciter regulator of the faceplate type with 60 steps and a continuously rated resistance of zero temperature coefficient permits close and stable regulation of power factor. If it is desirable to isolate the exciter from the motor during starting, a change-over switch is located alongside the circuit breaker and operated by the same ratchet handle. Instruments fitted at choice are main supply ammeter and volt-meter, exciter ammeter and volt-meter, power factor meter, wattmeter or watt-hour meter. Control gear of this type is suitable for motors up to 1 000 H.P. and 6 600 V. If desired, the exciter regulator may be adjusted automatically by a servo-motor under the control of a P.F. relay. Standard auto-transformer starters IV (b) or stator-rotor starters V (a) and V (c) can be modified to suit A.C. synchronous motors.

As already noted, the descriptions given above by no means exhaust the types of starters and controllers used for industrial motors. The supplementary devices most commonly required are those for reversing the motor, for dynamic braking, and for continued running at a 'creeping speed.' Control gear for traction motors is almost invariably of the drum type, the drum contacts being in the main circuit in the case of tramcars, but in the master control circuit of contactors in the case of multiple-unit trains and main line locomotives.

739. Liquid Controllers.—Liquid controllers are useful for starting and controlling A.C. motors, but metal resistances must be used with D.C. machines owing to the electrolytic corrosion and gassing produced by D.C. flowing through an electrolyte. The merits of liquid controllers include cheapness, simplicity, and indefinitely fine gradation of control, but it is necessary to observe certain precautions in their installation and use. For instance, the controller casing must be totally enclosed to exclude dust; provision must be made against 'creeping' and boiling of the electrolyte; and the contact plates must be shaped to give suitable gradation of resistance. Where the electrodes are lowered into the electrolyte, the raising and lowering gear should be self-sustaining and of such a gear ratio that the plates cannot easily be lowered too rapidly. It is desirable that definite metal-to-metal contact should be provided when the plates are in the 'resistance-out' position. A solution of soda is preferable to common salt, since the latter attacks iron. Liquid starters are in use for pressures up to 700 V

or higher, and for motors up to 1 000 H.P. or over. In the largest starters, the electrodes are fixed and the level of electrolyte is varied. For example, three electrodes (corresponding to the three phases of a slip-ring rotor) may be mounted in a chamber provided with an adjustable weir and placed over a sump tank. A centrifugal pump circulates electrolyte continuously from the lower to the upper chamber during working hours. If the weir be 'up,' resistance between the three electrodes is reduced to an extent depending on the setting of the weir and at a rate varying with the speeds of the pump or with the setting of a valve in its delivery pipe. On lowering the weir plate, extra resistance is inserted or the circuit is opened practically instantaneously. Too rapid removal of resistance is impossible in this type of controller; the electrolyte may be cooled by water pipes as well as by its own circulation; and a definite resistance corresponds to each weir-setting. A typical application of liquid controllers is in the rotor circuit of 3-phase colliery winding motors of the slip-ring induction type.

740. Flame-proof (Explosion-Proof) Gear.—A flame-proof (including explosion-proof) enclosure for a switch, circuit breaker or other control gear is one which will withstand, without injury, any explosion that may occur within it under the actual conditions of operation and rating (including overloads, if any); also, the enclosure will prevent the ignition of a surrounding inflammable mixture by transmitted flame. Such an enclosure may be 'hermetically sealed,' in which case it must be capable of resisting an internal pressure of, say, 150 lb. per sq. in. with an adequate factor of safety; or it may be vented by labyrinth openings, or by spring bolts in wide flanges, so that internal pressure is promptly relieved, yet the escaping gases are cooled to such an extent that they are incapable of igniting inflammable mixture outside. A practical objection to 'hermetic sealing' is that it leads to accumulation of condensed moisture ('sweating') by the action already explained in relation to wiring conduits (§§ 538, 544, Vol. 2). In a properly vented casing, there should be no trouble from condensation, and the excess internal pressure should never exceed 20 lb. per sq. in. The escaping gases are thoroughly cooled by travelling for a distance of $1\frac{1}{2}$ to 2 ins. between flanges or vent washers about 0.02 in. apart, and there is no danger in using air-break switch-gear inside such a casing. Oil-gauge glasses on oil-immersed switch-gear should be well protected, and preferably of

Triplex glass. Bolt holes for attachments to the body of the enclosure (as distinct from the flanges) should be 'blind'; otherwise, the enclosure will not be flame-proof if the bolt be missing.

741. Remote Control.—An excellent example of the capabilities of the 'remote control' and automatic acceleration of motors is to be found in the equipment used on electric trains operating on the multiple-unit system (§ 871). The switches in the motor circuits are of the solenoid-operated contactor type controlled through a multi-core control cable running the whole length of the train and connected to a master controller in the driver's cab. The rate of acceleration is governed automatically.

The principal features of a typical equipment of this sort are summarised below, the particular apparatus described being the Metropolitan-Vickers 'all-electric control.'

The main current flows from the positive collector shoe through the shoe fuses, junction box, main isolating switch, equipment fuse and circuit breaker to the main contactor switches and motors, returning via the motor frame to the running rails.

The equipment circuit breaker is a solenoid-operated switch with a series overload trip, and a separate shunt trip operated by the driver when required. Reversal of the train is effected by solenoid-operated drum switches in the main motor field circuits.

Automatic acceleration is provided by a combined current and time-controlled accelerating relay. This relay operates contacts in the control circuits and governs the sequence of closing contactors; it is so designed that the control contacts on the relay never break a circuit and therefore do not become burnt.

The motor current is handled by contactor switches, actuated by solenoids connected to the line by the master controller. Interlock contacts on the contactors ensure that they close in proper sequence.

In order that the several motors may share the load equally, the corresponding points in the control circuits on the various motor coaches are connected by a multi-wire 'train line' cable, running the whole length of the train and connected between coaches by jumper cables with special plug and socket connectors.

The main handle of the master controller has four operating positions: (1) Giving series connection of the motors with all resistance in circuit. (2) Bringing the automatic relay into action so that resistance is cut out step by step till 'full series' is reached. (3) Transferring the motors from 'full series' to parallel connection with all resistance in circuit. (4) Bringing the automatic relay again into action, so that resistance is cut out step by step till 'full parallel' is reached.

If the driver removes his hand from the handle of the master-controller for any reason, the handle rises, the control current is interrupted, and the emergency brakes are applied automatically. This feature is called the 'dead-man's handle.'

Normally, the handle of the master-controller is moved straight to the series or parallel position, as desired, and the motors then accelerate at a rate determined by the automatic relay. In order to obtain slower acceleration, the handle is moved from the first to the second position (or from the third to the fourth position) and immediately returned. Each time this is done, one step of resistance is cut out provided that the current has fallen to a pre-determined limit; otherwise, the auto-

matic relay again comes into action. In other words, the acceleration may be made slower, but cannot be made faster than that corresponding to the setting of the automatic relay.

The remote control of single motors and groups of motors is being used to an ever-increasing extent in industrial applications of all descriptions. Familiar examples are the press-button starting and controlling of the motors driving machine tools and printing presses. The details of the equipment can be varied indefinitely to suit individual requirements. The example described above illustrates some of the chief principles and methods applied. According to requirements, a simple on-and-off press-button switch may be used to actuate a single contactor or a series of interlocked contactors; or a 'master' drum controller, with a spindle carrying any required number of contact segments, may be used to connect two or more of a series of stationary contact blades in any desired sequence and combination. The electrical and mechanical details of drum controllers vary infinitely according to the purposes to be served and the power to be handled. Wherever a number of changes in connections have to be made in definite sequence and definite relative timing, this type of controller is probably the most convenient and reliable pattern available.

742. Automatic Control.—Essentially, an automatic motor-starter consists of devices for automatically and progressively changing connections—whether of starting-resistances, by cutting them out of circuit; of compensator tappings; or of phase windings (star to delta); and so on—in order to accelerate the motor from stand-still up to full-load speed. The rate at which this acceleration is effected may be governed by an adjustable timing device, or by the current actually taken by the motor. The permissible rate of acceleration depends upon the inertia of the motor and its connected load. If the interval of time between the successive advances of the starting switch is to be regulated automatically, the timing must be adjusted to suit the heaviest load and, this timing being fixed, it will be unnecessarily slow when the motor is starting against lighter loads. If, however, the starter is controlled by the motor current, so that a fresh stage of acceleration is commenced directly the current has fallen to a pre-determined value, then the motor is started more rapidly the lighter the load, and, under all conditions, the current is kept within the desired limits. Theoretically, the 'current limit' is the correct principle

on which to start motors, but it may result in excessively rapid acceleration on light loads and in failure to start (and possibly burning out of resistances or compensator windings) on heavy loads which cannot be accelerated within the pre-determined current limits, but which would be accelerated (with somewhat heavier current peaks) by a time-limit starter.

For example, a conveyor motor may fail to start or to accelerate at the normal rate on the first notches during cold weather, owing to the high static friction of the cold bearings. A time-limit starter would nevertheless bring the motor up to full speed in the prescribed time at the expense of heavier current consumption during acceleration, and the circuit-breaker or fuse would operate in the event of the current being dangerously high. A current-limit starter, on the other hand, might keep the motor stationary under such conditions, or cause it to accelerate so slowly that, although the current were kept within the prescribed limits, its prolonged flow would burn out the starting resistances or windings.

The details of construction and application of relays for controlling the rate of motor acceleration can be varied indefinitely. In one useful type, which combines both current-limit and plain time control, a solenoid connected in the control circuit has a plunger carrying a disc, which bridges and closes contacts in the next section of the control circuit when the plunger falls. A second winding, on the same magnetic circuit, is connected in series with the motor so that, although the control solenoid be de-energised, the plunger cannot descend till the motor current falls to a predetermined value. This provides the current-limit feature of the automatic control. A dash-pot or similar device also imposes a definite time lag on the descent of the plunger, so that, however light the motor load, the rate of acceleration of the machine cannot exceed a predetermined maximum. With this equipment, the motor is subject to a certain minimum time of acceleration, which is automatically prolonged if necessary to prevent the current from becoming unduly heavy. The limitation of the current is, however, only partial, for no definite limit is imposed upon the *maximum* current. A further step of acceleration is permitted directly the current on one step has fallen to a prescribed value; the exact value of the initial rush of current on the next step depends upon the load on the motor.

A typical fully-automatic control for a variable-speed D.C. motor comprises a contactor-type starter and a shunt-field rheostat actuated by a servo motor. The main motor is controlled by 'start' and 'stop' press-buttons and by 'raise' and 'lower' press-

buttons for speed variation, the latter starting the field-regulating servo motor in one direction or the other. Often it is sufficient to regulate the speed by hand, relying for press buttons only to start and stop the motor. If 'inching' is required, *i.e.* temporary running at very low speed for the purpose of moving parts of the driven machine into a convenient position, this may be obtained by means of a button which brings a contactor into action, connecting the D.C. motor armature to the supply in series with a suitable resistance. The motor runs at inching speed only whilst the inching button is held down. Similarly, equipment is available for the control of A.C. variable-speed motors, the auxiliary motor then shifting the brushes of the main motor or varying the rotor resistance, as the case may be.

743. Protective Devices.—The general principles and methods of providing protection against overload, low voltage and interruption of supply are mentioned in §§ 344, 355, Vol. 1. In certain fully-automatic installations it may be desirable for motors to start again directly normal supply voltage is restored, but, in general, the low-voltage protective gear of motors not only restores starting conditions, in regard to insertion of armature resistance, restoration of full field, and so on, but also opens the main circuit breaker so that the motor remains stationary until it is deliberately started again. A single no-voltage release protects a machine in the event of complete failure of supply, but it is impossible to protect against failure in one phase of a polyphase machine by a no-voltage release in each phase, because the defective phase remains charged by transformer action. An overload release in the rotor circuit of a slip-ring induction motor (without ring short-circuiting gear) protects the machine against interruption of one stator phase, as well as against ordinary overload. In modern control gear the main contactors often provide no-voltage protection (§ 738). Where special no-volt coils are used it should be ascertained that they do not overheat in continuous service and that their armature or plunger is not liable to stick.

In a 3-phase, 3-wire circuit with isolated neutral overload releases in two phases suffice, but a release in each phase is necessary if the neutral be earthed. Overload protection should be maintained during starting as well as during normal running. A combination of fuses and thermal overload-relays offers important advantages. The fuses ensure instantaneous interruption of supply

at a predetermined overload or on the occurrence of a short-circuit, and they can be designed to interrupt safely the high power behind a fault in a large central station system. The rating of the fuses is much higher than the overload which can safely be carried by the motor for any appreciable time, and it is the function of the thermal overload release, or other trip gear with inverse time element, to provide normal overload protection, as distinct from protection against abnormal overload during starting or under fault conditions.

An electromagnetic overload release, depending on the attraction of a plunger or armature by a coil carrying the motor current, does

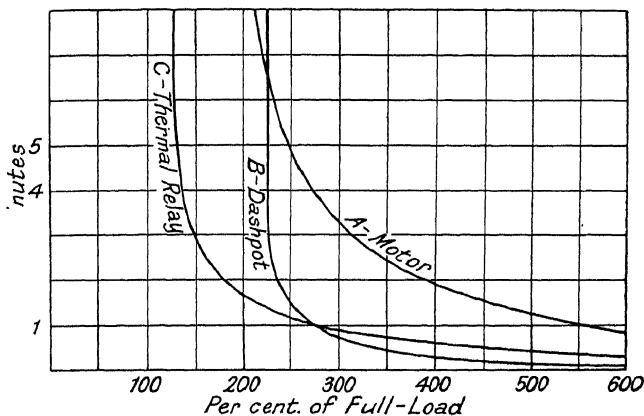


FIG. 383.—Overload protection with thermal and dashpot time elements.

not follow the law of heating of the motor, which is the factor determining the permissible overload in normal operation. A dashpot or other mechanical inverse time element may be provided so that the trip operates more rapidly the greater the overload on the motor. The ideal arrangement is to have a release which obeys the same law as the heating of the motor, and this can be obtained by using a suitably designed heating coil in conjunction with bi-metal strips which operate the trip gear at a predetermined temperature. This combination protects the motor against any dangerously prolonged overload, however small its actual value, yet it is not actuated by the transient rush of current during starting.

The advantages of the thermal-relay type of overload protection may be explained by reference to Fig. 383. If curve A

represents the time for which the motor could carry various loads without injurious heating, it is obvious that for safety the time-load curve of the overload release must be below *A* (so that, for any load, the release operates before the motor reaches a dangerous temperature), while, for convenience and maximum utilisation of the motor, the release characteristic should be of the same general form as the curve of motor heating. Curve *B*, referring to an electromagnetic tripping device retarded in its action by a dashpot, does not conform to these requirements; in the case shown, it is set for $2\frac{1}{4}$ times full-load,* and affords no protection against smaller loads, however long maintained; on the other hand, it disconnects the motor almost instantly if the current reaches 5 or 6 times full-load value, hence the release must be put out of action temporarily if the motor is to be started straight across the line. The thermal relay, however, (curve *C*) protects the motor against prolonged overloads down to about $1\frac{1}{4}$ times full-load, and yet will allow, say, 6 times full-load current to flow for 15 seconds before disconnecting the motor, thus allowing for permissible rushes of starting-current without even a temporary sacrifice of protection. The development of heat in both the thermal relay and the motor varies with the square of the current flowing, and it is possible to adjust the cooling facilities of the thermal relay so that the temperature of the latter is always approximately in a predetermined relation to the temperature of the motor, so that equal protection is obtained whether the motor is heated by a temporary heavy current or a sustained moderate overload.

With the increasing adoption of 'continuous' methods of manufacture and operation there is, in most industrial establishments, a sequence of conveyors carrying raw material or component parts for a considerable distance. In this, or any other case where the stoppage of one motor would break the continuity of action of a series of machines, it is desirable to arrange that the stoppage of any motor automatically stops all the other motors on the feeding side, thus preventing the piling up of material at the place of breakdown, whilst allowing motors ahead of the break to continue running to clear away the material already on their conveyors,

* This value can be varied as desired, and the shape of curve *B* can be altered to some extent, but the general features of the two methods of protection remain as stated.

etc. All that is needed for such purposes is a series of electro-magnetic switches, one in each motor circuit; each motor holds 'in' the switch in series with the preceding machine of the group.

Increasing use is being made of *thermionic valves* (§§ 418 *et seq.*, Vol. 2) for the control and protection of motors in a great variety of applications. The advantages of valves for this purpose include remarkable sensitivity, instantaneous response, and the complete absence of mechanical moving or wearing parts. Hitherto the valve has generally taken the place of an electro-magnetic relay, but, with improvements in the construction of valves, there is an increasing tendency to connect them directly in the circuits controlled. *Photo-electric cells*, the electronic conductivity of which is established by light falling upon the cathode, are used, *inter alia*, in conjunction with three-electrode valves, to control machine tools and conveyors, and to secure the accurate 'registering' of printed materials in wrapping machines. The existing applications of electron tubes of all types are too numerous to mention; their possibilities should be considered wherever the control of electrically driven machinery is concerned.

744. Limitation of Starting Demand of a Group of Motors.

—There are many cases in which it is desirable to prevent large motors being started simultaneously. The heavy rush of current, usually at low power factor in the case of A.C. motors, may be of minor importance where supply is taken from a power station of very high generator-capacity, but there are many loads—*e.g.* colliery winding, heavy transporter bridges, cranes, etc.—such that the simultaneous starting of several motors would produce appreciable disturbance in the supply from a medium-sized station. Other instances in which it is desirable to avoid simultaneous starting of heavy loads are: (1) where supply is taken under a maximum demand tariff, and avoidable peak loads are therefore specially objectionable; (2) where supply is taken from a generator driven by an extraction or back-pressure turbine serving a steady heating load or manufacturing process; in this case it is very undesirable to subject the turbo-generator to avoidable fluctuations in load.

One method of equalising the demand on the supply system, in all such cases, is by using fly-wheel storage (§ 828), but the cost of the special equipment then involved can sometimes be avoided if it is permissible to delay the starting of any one of the

large motors until no other one of them is being started, and if it is practicable to give each motor operator an indication of when he may or may not start his machine. A simple way of doing this* is by using a small synchronous motor, near each large motor, to drive through reduction gearing a pointer rotating over a disc marked with black and white sectors. If there are four large motors to be considered, the signalling disc for each is three-fourths black and one-fourth white, the white sectors being displaced 90 degrees with regard to each other. When starting-up or resuming work after a shut-down, each indicating pointer is started from zero by closing a coupling between its servo-motor and the reduction gear at a moment indicated by telephone from a central station. Thereafter, the pointers at the several motor stations necessarily keep in step, no matter how far apart the machines may be, the speed of the synchronous servo-motors being fixed by the supply frequency of the system. So long as each driver starts his machine only while the pointer is over the white sector of the dial, it is impossible for two large motors to be started at once. In order to reduce the interval of waiting between two 'starting permissible' periods, it is only necessary to divide the white sector into two equal parts situated diametrically opposite to each other on the disc. This system of control is applicable to machines any distance apart, provided that telephonic or other communication is available for synchronising the pointers.

745. Bibliography.—(See explanatory notes, § 58, Vol. 1.)

OFFICIAL REGULATIONS.

See Chapter 41 in this volume.

STANDARDISATION REPORTS, ETC.

(1) *British Standard Specifications.*

No. 88.—Electric cut-outs, type O (rated carrying currents not exceeding 100 A and declared voltage not exceeding 250 V to earth).

No. 109.—Air-break knife switches and laminated brush switches for voltages not exceeding 660 V (excluding totally enclosed and flame-proof types).

No. 110.—Air-break circuit breakers for voltages not exceeding 660 V (excluding totally enclosed and flame-proof types).

No. 115.—Metallic resistance materials for electrical purposes.

No. 116.—Oil-immersed switches and circuit-breakers for A.C. circuits.

No. 117.—Drum starters for electric motors (D.C. and A.C., 2- and 3-phase induction with slip-rings).

Described by H. Voigt, *Zeits. des Verein. deutsch. Ing.*, March 5, 1927, p. 338.

- No. 118.—Drum controllers and resistances for use therewith for D.C. and A.C. slip-ring motors.
- No. 123.—Face-plate controllers and resistances for use therewith for D.C. and A.C. slip-ring motors.
- No. 124.—Totally enclosed air-break switches for voltages not exceeding 660 V.
- No. 126.—Flame-proof air-break switches with or without fuses (A.C. and D.C. not exceeding 660 V) suitable for the coal-mining industry.
- No. 127.—Flame-proof air-break circuit breakers (A.C. and D.C. not exceeding 660 V) suitable for the coal-mining industry.
- No. 129.—Contactor controllers and resistances for use therewith for D.C. and A.C. slip-ring motors (excluding traction controllers).
- No. 130.—Totally enclosed air-break circuit breakers for voltages not exceeding 660 V.
- No. 140.—Liquid starters for electric motors (D.C. and A.C., 2- and 3-phase induction with slip-rings).
- No. 141.—Switch starters (star-delta and series-parallel) for A.C., 2- and 3-phase induction motors without slip-rings; from 2 to 40 h.p.
- No. 142.—Electrical protective relays.
- No. 147.—Multiple switch starters for D.C. motors.
- No. 155.—Contactor starters for electric motors (D.C. and A.C. 2- and 3-phase induction with slip-rings).
- No. 158.—Marking for switchboard bus-bars and connections (including arrangement for 3-phase systems).
- No. 159.—Bus-bars and connections of bare copper or aluminium.
- No. 160.—Slate slabs for electrical purposes.
- No. 162.—Electric power switchboards for indoor installations up to and including 33 000 V.
- No. 167.—Hand-operated auto-transformer starters for A.C., 2- and 3-phase induction motors without slip-rings.
- No. 194.—Switchgear equipments for D.C. circuits when the voltage does not exceed 660 V.
- No. 195.—Switchgear equipments for 3-phase A.C. circuits not exceeding 33 000 V.
- No. 229.—Flame-proof enclosures for electrical apparatus (for mines and other places where explosive atmospheres may be encountered) and tests for flame-proof enclosures.
- No. 246.—Face-plate starters for D.C. motors.
- No. 247.—Face-plate rotor starters for 2- and 3-phase induction motors with slip-rings.
- No. 279.—Flame-proof type plug and socket, heavy duty.
- No. 280.—Field rheostats for generators, motors, synchronous converters and balancers.

See also § 712.

Books.

- Motor and Dynamo Control, W. S. Ibbetson (Spon).
 Controllers for Electric Motors, H. D. James (Van Nostrand).
 Electric Control Gear and Industrial Electrification, W. Wilson (Oxford).

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- Electric Motors and Control Systems, A. T. Dover (Pitman).
 D.C. Industrial Motor Control, A. T. Dover (Pitman).
 D.C. Traction Motor Control, A. T. Dover (Pitman).
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 Industrial Electric Motor Control Gear, W. H. J. Norburn (Pitman).

I.E.E. PAPERS.

- The Design of Liquid Rheostats, W. Wilson. Vol. 60, p. 196.
 Electric Motor Starters, J. Anderson. Vol. 60, p. 619.
 Operation of Induction Motors in Cascade, H. Cotton. Vol. 61, p. 284.
 A Novel Method of Starting Polyphase Synchronous Motors, E. V. Clark.
 Vol. 62, p. 878.
 The Design of Electrical Plant, Control Gear and Connections for Protection against Shock, Fire and Faults, H. W. Clothier. Vol. 63, p. 425.
 A New System of Control for Electrically Driven Winches and Cranes, J. Bentley. Vol. 64, p. 567.
 The Starting of Single-Phase Induction Motors, F. A. Laufer. Vol. 65, p. 160.
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MISCELLANEOUS.

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 Hints on Rectifying Faults in Motor Control Gear. An admirable booklet issued by George Ellison, Birmingham.

ELECTRIC DRIVING.

746. Applications of Electric Motors.—For reasons discussed fully in the next paragraph electric motors are now used for practically every driving purpose, in sizes ranging from a small fraction of 1 H.P. up to some tens of thousands of horse-power, and in situations ranging from total immersion in water to explosive or fume-laden atmospheres and the highest temperatures which insulating materials will withstand. Some of the principal applications of electric motors are mentioned in this chapter, and data useful for estimating purposes are given. Further information on specific applications is to be found in Chaps. 31-37 inclusive, but it must be emphasised that the methods described and the figures given are only to be regarded as typical, for the flexibility of electric driving is such that practically any conditions can be met.

747. Advantages of Electric Driving.—The arguments in favour of electric driving may be considered under three main headings: (1) As regards the utilisation of primary energy. (2) The ease and efficiency with which electrical energy can be applied wherever it is required. (3) The accuracy with which power costs can be determined and economical production maintained where electric driving is employed.

(1) *Utilisation of Primary Energy.*—The electric motor is not a prime mover; it cannot utilise the kinetic or latent natural energy of wind, water or fuel, but must be furnished with a supply of electricity which, for all but weak currents, requires a generator driven by a prime mover. Nevertheless, as a matter of experience, the overall efficiency of electrical generation, transmission and re-conversion to mechanical energy at the motor is often higher than that of purely mechanical transmission from a prime mover through lineshafts, belts, ropes, gears, etc. Even in private plants, where a prime mover is used, whichever system of transmission be employed, the electrical system is generally at least as efficient as

mechanical driving; and, even if the frictional losses of the latter be less than the distribution and double-conversion losses of the electrical system, the difference is more than counterbalanced by the advantages cited at (2) and (3) below. Where central station supply is used, the higher efficiency of large generator sets constitutes a further advantage of electric driving compared with mechanical driving from private plant. In such a case, too, the consumer is saved the expense of installing and operating prime movers and generators of his own, and can increase his demand to any desired extent, either instantly or on short notice if the increase is so considerable as to necessitate the connection of additional cables.

So far it has been assumed that the comparison is between electrical and mechanical power alone. Where heat is also required, whether for warming buildings or for manufacturing processes, the economic possibilities of combined power and heating systems should be considered.

One of the advantages of electric driving is the manner in which it facilitates the combined operation of power and heating services. As explained in §§ 176, 188, Vol. I, a condensing steam engine or turbine rejects to its condensing water 50 or 60 % of the heat developed by the combustion of fuel below the boilers. By exhausting steam from the prime mover at a back-pressure suiting the heating or process requirements, and extracting some steam at an intermediate pressure as well, if necessary, the condensate loss can be eliminated more or less completely. The prime mover is then used as a power-producing reducing-valve giving mechanical power at the cost only of the extra fuel needed to generate steam at the pressure and temperature of the engine or turbine admission instead of at the pressure and temperature at which it would, in any case, have to be produced for heating and process purposes. The latent heat of vaporisation, constituting by far the greater part of the total heat of steam, cannot be recovered in power generation but can be utilised in heating service. By appropriate choice of the initial conditions of the steam, and by using steam accumulators where necessary, the power and heating loads can generally be balanced satisfactorily. The advantages of combining power and heating services are essentially the same whether the power be used for direct mechanical driving or for generating electricity, but in practice electric driving often enables the com-

bination to be effected where it could not conveniently be practised with mechanical driving owing to the distance between the component parts of the plant. With electric transmission and driving, there is no need for the power and heating equipment to be in the same building, or even on the same premises. The possibility of co-operation on these lines, between several different establishments in the same district, should be investigated; it has already been found practicable in a number of instances.

Though an industrial user of power alone may find it preferable to purchase electricity from a central station, rather than add to his investment and responsibilities by laying down private generating plant, no central station which rejects exhaust heat can compete with even a small private plant which combines and balances its power and heat services. The relative advantages of private generation and purchase of energy are discussed in § 185, Vol. 1; to the remarks there given it may be added that a main unit in a private generating plant may sometimes have to be kept running, at low load and poor efficiency, in order to supply a few motors, whereas the smallest motor connected to central station supply mains operates at substantially the same overall efficiency when it is used alone as when all the machines are running. The deciding factor, however, is the average cost per H.P.-hour during the week, month or year, and this must be estimated for each individual establishment, and for each of the possible systems of supply and operation.

(2) *Distribution and Application of Power.*—Where electric driving is employed, the driven machines can be arranged for convenience and efficiency in the manufacturing processes concerned, without any regard to how power is to be brought to them. Mechanical driving involves an inflexible and cumbersome system of line- and counter-shafts, with belts, ropes or gears, but electric power can be taken wherever a cable can be run, and the motor can be placed wherever it can do its work to best advantage. Rearrangements or extensions of plant can be made at any time and in any direction by merely moving or extending the distribution cables.

Either group or individual driving may be used as desired (§ 748). The elimination or reduction of over-head shafts and belts improves working conditions in the shop, and may effect anything from 20 to 50 % saving of power compared with complete mechanical driving, not to mention the saving of time in repairing broken belts. The small I^2R loss in electric cables, from 2 to 5 % or so,

according to the length of the circuit and the amount of copper used, is much less than the loss by condensation in steam pipes where scattered steam engines are used, as in old collieries, calico-printing works, etc.; it is also less than the frictional loss in long lines of shafting and belts, and less than the loss by friction and leakage in compressed air pipes.

Power can be developed at any desired speed and torque where electric motors are used, and it is found that owing to the extreme regularity of the turning moment of an electric motor, it is possible to increase the speed and output of machinery by from 10 to 20 %. In textile machinery the slight changes of angular velocity of the flywheel, during each revolution of a mill engine, are enough to affect the working and to necessitate a reduction in the average speed of driving. Any desired form and range of speed control can be applied to machines which are driven individually by electric motors. Automatic control, to meet practically any requirements, can be actuated by electric relays which are both sensitive and reliable; such control is applicable to mechanical gear, but the full possibilities are only realised when the driving as well as the control is effected electrically. Reversible and interlocked drives are easily arranged where electric motors and switchgear are employed.

The power and speed characteristics of the various types of electric motors can be adapted to those of any particular load. For example, decreasing speed with increasing load may be obtained as a matter of expediency (*e.g.* by the use of series motors for traction purposes) or in order to utilise flywheel storage (§ 753); further information on the adaptation of motors to loads is given in § 749.

Isolated machines, or those which have to be used when others are idle, can be driven economically by electric motors but not by mechanical transmission of power.

(3) *Efficiency-Control and Determination of Power Costs.*

—One of the most important advantages of electric driving lies in the ease with which the energy consumption of a shop, or an individual machine, can be determined continuously at negligible trouble and expense. The power costs per unit of manufacture can thus be ascertained and, what is most important, any irregularity can be at once detected and its cause ascertained. Indicating ammeters afford a useful guide to the operation of individual machines, but recording or integrating watt-hour meters are necessary if the energy consumption is to be determined. These

may be fitted individually to the more important motors, but, in other cases, one or two meters may record the consumption of all the machines in a shop or department. A daily or weekly record of energy consumption should be kept; this will facilitate the allocation of power costs and will provide a general indication of the output from the department, the energy consumption decreasing if machines are idle. On the other hand, any marked increase in energy consumption, unless it is due to overtime working or some other easily ascertained cause, such as a rush of heavy work, is probably due to some defect or improper adjustment in the machinery. If this is suspected, it is a simple matter to connect a portable watt-meter in circuit with each motor in turn, test-terminals and detachable links being provided for this purpose when the machine is installed. The trouble can thus be located and remedied promptly where, otherwise, serious damage or long-continued waste of energy might occur.

As a means of recording machine operation, contacts may be arranged so that they are closed when, and only when, the machine is productively employed. The design and arrangement of these contacts must be adapted to each type of machine, and it must be impossible for them to be tampered with. Each contact is in one of the circuits of a multiple recorder which draws a line on a moving band of paper, calibrated in hours, as long as the machine is actively employed. This supervisory system is, of course, equally applicable, whatever the method of driving the machines.

The cost of electrical energy for driving purposes is often so low in relation to the total costs of production that it may seem an unnecessary refinement to pay much attention to its actual value. The fact is, however, that the consumption of energy in any electrically-driven plant stands in a definite relation to the overall efficiency of the driven machines and the volume of their output. The readings of the electricity meter therefore constitute a valuable index of efficiency and output.

748. Group versus Individual Driving.—Strictly speaking, electric driving is necessarily individual driving, for, whenever a group of machines is driven by a single motor, there is necessarily a mechanical transmission between the motor and the driven machines. The more extensive the group, the more nearly do the characteristics of the drive approach those of mechanical driving from a steam engine or other prime mover. The use of a separate

motor for each driven machine enables full advantage to be taken of the flexibility and convenience of electric driving, and each machine can be placed wherever it can be used most effectively. Group-driving, on the other hand, is only economically applicable to machines situated comparatively close together and within easy reach of one or a few lineshafts. Group-driving naturally offers the easiest means of 'electrifying' an existing mechanically-driven establishment, an electric motor being direct- or belt-coupled to each lineshaft or pair of lineshafts; or the lineshafts being divided into lengths with a driving motor for each. This arrangement approximates more nearly to the original mechanical drive, the larger the groups retained.

The main argument in favour of group-driving is the saving effected in the first cost of the motors and control gear required; against this must be set the cost of shafting, pulleys, gears, safety-guards, and other equipment needed to distribute power from the group motor to the driven machines. As shown by Tables 128, 129, § 711, small motors are relatively more costly than those of higher power. Ten 1 H.P. motors may cost about three times as much as a single 10 H.P. motor, and in group-driving it is quite likely that a single $7\frac{1}{2}$ H.P. motor would suffice where ten 1 H.P. motors would be needed for individual driving. The matter is one of diversity factor (§ 262, Vol. I). A motor driving a single machine must be capable of developing the maximum H.P. required by that machine, but the maximum H.P. required by a group of machines is almost invariably considerably less than the sum of the individual maxima. Conditions vary widely, but in an average case it may be found that twenty 10 H.P. individual motors can be replaced by a 100 H.P. group motor capable of withstanding 50 per cent overload temporarily. The higher the diversity factor of a group of machines, the greater the opportunity for reducing capital expenditure by group-driving, but only those machines should be grouped which will provide a reasonably uniform load during the whole time the motor is running. In other words, the grouping should not be such that the driving motor has to be run for considerable periods in order to drive one or a few small machines; under such conditions the group motor would operate at very low efficiency and (if an A.C. machine) power factor.

There are certain frictional losses, in the mechanical transmission of every group-drive, which remain almost constant, regardless of

the number of machines actually in service. The effect of these losses on the overall efficiency becomes more serious, the smaller the number of machines in action.

For example, suppose that eight machines, each requiring 2 kW on full-load, are driven by a group motor which absorbs 3 kW when driving the transmission shaft and loose pulleys alone, the eight machines being out of action. The power absorbed by the group-drive itself is then 50 % greater than that required to drive one of the machines at full-load by a direct-coupled individual motor. With one machine in action from the group-drive the input to the group motor must be about $3 + 2 = 5$ kW or $2\frac{1}{2}$ times the power required for individual driving of a single machine; the efficiency of the group drive in this case is about $2/5$ or 40 % (leaving out of consideration the efficiency of the motor itself which is higher for a small, fully-loaded individual motor than for a larger partially-loaded group motor). When four machines are in action, the group motor absorbs about $3 + (4 \times 2) = 11$ kW, and the efficiency of the group-drive is about $8/11$ or nearly 73 %; whilst, with eight machines in action, the group motor absorbs about 19 kW and the efficiency of the group-drive is approximately $16/19$ or 84 %. Actually, the mechanical losses in the transmission increase somewhat with the load, but this increase is far more than compensated by the increase in the efficiency of the group motor at higher loads. With individual motors, any number of the eight machines considered could be driven at full-load with the same efficiency, *viz.* that of the individual motors.

In addition to the capital economy effected by the group-driving of machines of low or medium H.P., there will often be an appreciable reduction in running expenses, for the efficiency of a large motor running at a fairly steady load, amounting to, say, 75 % of its rating, is appreciably higher (possibly 5 or 10 %) than that of a small motor running at a variable output, often 50 (or less) % of its rating; also, the supervision and maintenance of a number of small motors cost more than those of a few larger machines. The power factor of a group motor is generally higher than the average P.F. of a number of individual motors (§ 158, Vol. 1).

On the other hand, a breakdown in a group-motor or its transmission system involves shutting down the whole group of driven machinery; this is a serious consideration. Emergency stop buttons can be provided so that a group motor can be stopped in emergency from one of any desired number of places, but, in the event of such a stop, the whole group of machines is thrown idle, and, owing to the inertia of the many moving parts, the stop cannot be as rapid as in an individual drive.

Again, group-driving involves retention of lineshafts and belting which can be more or less completely eliminated by

individual driving. Apart from the noise and obstruction of lineshafts and belts there is a waste of energy by friction. Individual driving does not always eliminate mechanical speed reduction by belt, chain or gear, the economic speed of small electric motors being often higher than the desired speed of the driven machinery, but, even where such speed reduction is required, it does not involve so much frictional loss as a lineshaft and its belts. Also, there need be no torsional 'whip' in an individual drive, but this is inevitable in a lineshaft under variable load where it causes appreciable fluctuations in speed. For this reason, a higher speed, with an increased output of higher quality, can often be maintained by using individual instead of group-driving; the driving of looms is a case in point.

Summarising the preceding remarks, it may be said that group-driving makes possible considerable economies where a fairly steady average load is available from machines conveniently situated and making no stringent demands as regards constancy of speed. On the other hand, individual driving is advisable where machines are scattered or not in line: where loads are irregular or intermittent; and where constancy of speed and flexibility of speed control are important. If, however, these possibilities of individual driving are to be realised, the motor must be chosen to suit the characteristics of the load, for it is subjected directly and exclusively to them. For example, a 100 % overload on a machine normally absorbing 5 H.P. doubles the load on a motor driving it individually, but represents only 10 % increase in load on a group motor which is developing 50 H.P. prior to the moment considered.

Heavy machinery should always be driven by individual motors, there being then no advantage in group-driving but, on the contrary, every reason for giving each machine (and even each motion of the machine) its own motor.

749. Importance of Load Characteristics.—Though the point is often overlooked, it is desirable that the characteristics of every electric motor should resemble as closely as possible, or be easily and efficiently adjustable to those of the load which it drives. This is particularly important in the case of individual driving, because the motor has then to deal with the requirements of a single machine, without the equalising effect of a group load (§ 748). The motor characteristics must correspond to those of the load in

certain respects; for example, the starting torque must be at least equal to that required to set the load in motion (unless the motor can be started light, by means of a loose pulley, friction-clutch, or equivalent device). Similarly, the motor must be capable of developing the maximum output required by the load, and for the desired period. In addition, and these are the less obvious requirements, the motor must be capable of developing the desired torque and horse-power throughout the range of speed regulation desired, and, for capital economy and operating efficiency, its characteristics should approximate as closely as possible to those of the load throughout the range of working conditions.

Where heavy overloads may arise allowance must be made for the fact when choosing the motor; conversely, a smaller machine may be selected for a service in which no serious overload is possible, *e.g.* driving a compressor at constant speed with constant delivery pressure.

The speed, and the range and degree of speed control required, affect the selection of motors, as explained more fully in § 750.

Where there are cyclic variations in the torque of the load, *e.g.* in compressors, and synchronous motors are to be used, care should be taken that the frequency of these variations does not coincide with the frequency at which the motor tends to 'hunt' (§ 679).

In low power, high-speed machines, the normal torque is small, hence any increase in the torque demanded by the load itself, or imposed by increased friction in the glands, etc., of the driven machine, may represent a serious increase in the horse-power required from the driving motor. If the overload capacity of the motor be chosen to allow for this, the machine becomes larger and more expensive; also, it operates under normal load at lower efficiency and power factor. The alternative is to use a motor suitable for the normal load, pay special attention to frictional and other adventitious loads, and use fuses or an overload release setting which will shut down the motor directly the legitimate maximum load is exceeded. This may be the best course so far as frictional overload is concerned (the consequences of this being specially serious at high speeds), but in order that production may not be hindered directly the load itself is increased, it is probably best to install a motor of liberal overload capacity and cover the frictional risk by close supervision.

It is not always realised how great an effect the torque-speed

characteristic of the load has on the H.P. required to drive it. This point is illustrated by Fig. 384. In the case of a constant-torque drive, *e.g.* a frictional load, or a reciprocating pump delivering against constant pressure, the horse-power (proportional to torque \times speed) varies linearly with the speed, as shown by curve *A*. If the torque were to vary in direct proportion to the speed, the horse-power would vary with the square of the speed, *see* curve *B*. The torque required by a fan, centrifugal pump or propeller varies with the square, and the horse-power with the cube of the speed

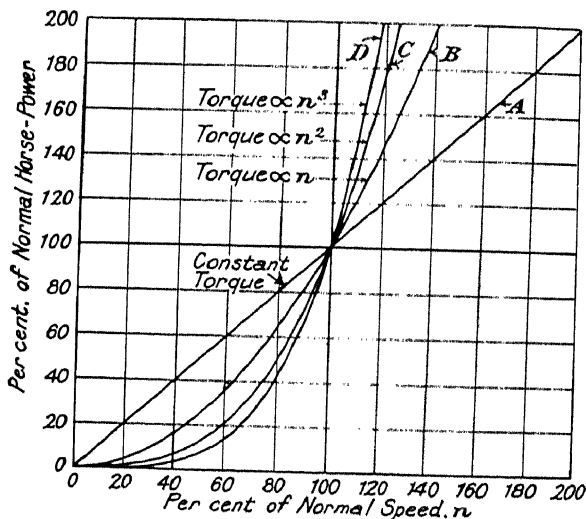


FIG. 384.—Effect of torque-speed law on H.P. required for driving at various speeds.

(curve *C*); and in a case where the torque varies with the cube the horse-power varies with the fourth power of the speed (curve *D*). A speed variation of $\pm 20\%$ involves $\pm 20\%$ variation in H.P. in the case of a constant-torque drive, but from about 73% above to nearly 50% below normal H.P. when the torque varies with the square of the speed.

Clearly, if the speed of a driven machine is to be varied, for whatever reason, it is essential that the effect of this change on the torque and horse-power should be known, in order that the driving motor selected may meet the requirements. In particular, it must be certain that a variable-speed motor is capable of developing

the requisite horse-power on its lowest speed; and the motor must be capable of carrying the current needed to develop the desired torque when running with reduced field.

For best results, primary consideration should be given to the conditions which must be fulfilled in order that maximum output or service may be obtained from the driven machine. Whatever these requirements, they can be met by electric driving, and it is almost invariably better to obtain maximum production or highest service than to obtain a smaller return at less cost for equipment, energy, or both.

750. Choice of Motor and Drive.—The selection of an electric motor for any industrial purpose involves consideration of mechanical features and characteristics (speed, reversibility, coupling or gearing, etc.) as well as the electrical type of the motor itself. Mechanical and electrical reliability is of the highest importance; even if the safety of men is not involved, a single breakdown is likely to cost more by interruption of output than the difference between the capital or running costs of any alternative motors over a long period. In some instances considerations of reliability will dictate the use of one type of motor or drive in preference to another capable of performing the same duty, but the reliability of all electric motors by reputable makers is such that the choice between them can usually be based on their normal operating characteristics, with full assurance that these characteristics will be maintained in service.

The following paragraphs are devoted to mechanical considerations, including couplings, gears, flywheels, etc. (§ 751); the choice of motor horse-power (§ 752); the selection of the electrical type of motor (§ 753); and notes on the influence of electricity-supply conditions and restrictions (§ 754).

751. Mechanical Considerations in the Selection of Motors and Drives.—The first point to be decided is whether *group or individual driving* should be employed, and this question has already been discussed (§ 748). The next decision concerns the *type of enclosure* to be adopted. This is settled by the conditions under which the motor is to be used; the standard types of enclosure are specified in § 670, which will enable the appropriate type to be selected in any particular case.

For most purposes a *horizontal-shaft motor* will be employed, but the possibility of a *vertical-shaft motor* being more suitable

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should be considered. A vertical motor often saves space and avoids the use of bevel gearing, e.g. in driving a centrifuge or hydro-extractor, some of the motions of a planing machine, a vertical shaft grinding machine, and so on. In other instances, as when a pump has to be driven in a sump, a vertical motor can be located in a dry, accessible position whilst driving the vertical shaft directly; or a vertical submersible motor may be coupled directly to the pump and submerged within a small bore-hole or other confined situation. The whole weight of the rotating parts of the motor and driven machine can be carried by a suspension thrust bearing at the top of the vertical motor; this is often an important advantage.

The actual *dimensions* of the motor will depend primarily upon its horse-power and speed, and to a less extent upon its type and enclosure. In the interests of capital expenditure and economical maintenance, standard sizes of motors should be used wherever possible, and, when new driven machines are being designed, the location of shafts and the space provided for motors should be, as far as possible, consistent with the dimensions of standard motors. A good deal of unnecessary expense and inconvenience are occasioned by ignoring this principle. Co-operation between machine and motor manufacturers is particularly important when the machine is to be driven individually by a motor built into or on to the machine itself.*

The choice of a motor is influenced materially by whether *speed variation* is required and, if so, by the range and gradation of control demanded. In some cases speed variation is not essential but is preferable, e.g. the output of a fan can be reduced more economically by speed variation than by throttling, and if a compressor has to run at reduced output for a considerable period it is more economical to lower the speed than continually to 'unload' the compressor by closing its suction or opening its delivery valve. The influence of speed-variation requirements on the selection of motors is further discussed in § 752.

* For example, a certain firm has standardised squirrel-cage motors with stator laminations welded together under pressure to eliminate rivets and the stator casing, thus reducing the diameter to a minimum. These motors are intended for wood planers and similar wood-working machines; the stator is built into the machine frame and the rotor is coupled directly to the tool spindle. Motors of this type developing 3 and 5 H.P. at 3 600 r.p.m. are $6\frac{1}{2}$ ins. in external diameter, and $4\frac{1}{2}$ ins. and 6 ins. long respectively. The possibility of using such machines obviously depends upon timely consideration of dimensions.

Whether the motor speed is to be constant or variable, it is generally advisable to use a *high-speed motor* in preference to a low-speed machine, without, however, going to extremes which would necessitate a motor of special construction or a reduction gearing of abnormally high ratio. Within commercial limits, a given motor carcass can be wound to develop four or five times the horse-power at its maximum speed that it can develop at its lowest speed. For a given output, high-speed motors are materially lighter, cheaper and usually of several per cent. higher efficiency (and power factor, if A.C.) than low-speed motors.

For example, the efficiencies and power factors of a certain series of 15 H.P., 200 V, 50-cycle, 3-phase induction motors of various speeds, are as follows:—

Speed, R.P.M.	500.	1 000.	1 500.	2 000.	3 000.
Full-load efficiency, %	82	85	87	87.5	87
Full-load power factor	0.80	0.86	0.89	0.90	0.90

Even where it is necessary to employ high-ratio reduction gearing between the motor and the driven machine, the cost of this gearing and of the frictional loss therein is fully justified by the saving on the high-speed motor. Machine-cut gearing, properly heat-treated, is relatively expensive, but its mechanical efficiency may be as high as 98 %. For very high speeds, A.C. synchronous and induction motors are more economical in upkeep than commutator motors (whether D.C. or A.C.), but, at ordinary speeds, the difference is not serious provided that the correct grade of brushes is used in the commutator machines.

Where *speed reduction* is required between the motor and the driven shaft, the choice usually lies between belt, rope, chain, and toothed gearing, with hydraulic transmission as a valuable alternative for special cases.

If the range of speeds required at the driven spindle is greater than can economically be provided by field variation, or other electrical means, stepped or conical belt pulleys or change-speed gearing may be used between the motor and spindle to provide two or more basic speeds, each of which can be varied by motor control (over a range of from $1\frac{1}{2}$ to 3 : 1) so as to cover completely the whole range desired. Where only a single speed ratio is required between the motor and the driven shaft, the actual speed still

being varied electrically if desired, a flat belt drive may be employed, with a jockey or 'Lenix' pulley to prevent belt-slip, if the shaft centres be close. Alternatively, a belt of trapezoidal cross-section may be used, running on grooved pulleys: this arrangement is cheap and satisfactory in such cases as that of a certain washing machine where a $\frac{1}{4}$ -H.P. motor with a pulley of $2\frac{3}{4}$ ins. effective diameter drives a $9\frac{1}{2}$ -in. pulley, obtaining a 4 : 1 speed-reduction with shaft centres only $10\frac{1}{2}$ ins. apart. For drives of higher power, a silent chain may be used to obtain an efficient and compact drive of high-speed ratio. An important advantage of belt driving is the slipping of the belt which reduces the shock and overload on the motor in the event of abnormal resistance being encountered on the driven shaft. Where a positive drive is obtained through a chain or gear-wheels, protection should be obtained by the use of a friction clutch; or the drive may be through an easily replaceable shear pin. Nothing but a permanent, positive drive should ever be used with a series motor: the slipping of a belt or the fracture of a shear pin would allow such a motor to race. Hydraulic variable-speed transmissions are smooth and flexible, but usually expensive.

Motors fitted with a raw-hide pinion and cast-iron spur wheel, with 7 : 1 gear ratio in small sizes and 5 : 1 in larger sizes, form very convenient units for low-speed driving. Still greater reduction may be obtained by the use of worm gearing (as, for example, in lifts), the gear ratio being then as high as 25 or 30 : 1. The steel worm drives a phosphor-bronze worm-wheel and runs in an oil bath. For the sake of efficiency, it pays to use a worm gear which is cut very accurately and built from the best materials available. The cost of such a gear is considerable, but there is a correspondingly substantial saving in the cost, size, and weight of the motor itself.

An improvement of 1 % in the *efficiency of a mechanical transmission* is obviously as desirable as 1 % added to the efficiency of the motor, so far as reduction of the power bill is concerned, yet the savings which can be effected by such easy means as the proper choice of pulley sizes, correct belt tension, care in the selection and erection of gearing, and the use of ball or roller bearings, are often overlooked.

The limiting range of *speed variation* by electrical means is usually about 4 : 1 (sometimes 6 : 1), and even this involves a

relatively heavy motor if full, or nearly full, H.P. has to be maintained at the lower speeds. If full H.P. has to be maintained at $\frac{1}{4}$ -speed by a direct-coupled motor, the torque must be four times that developed at full speed; this subjects the motor to correspondingly increased mechanical stresses, and the electrical and magnetic circuits of the motor must be of such dimensions that the requisite current and field can be used to obtain the higher torque. On the other hand, where the desired range of speed is obtained by variable-ratio gears, the higher torque at the lower speeds is obtained by the purely mechanical action of the gears themselves, the motor continuing to run at high speed and low torque. For this reason, change-speed gearing should be used, if possible, where full power is required over a wide range of speed, a moderate degree of speed variation being provided in the motor itself, to secure continuous gradation. If the H.P. required decreases with the speed it is neither difficult nor costly to provide a wide range of speed variation by electrical regulation.

An interesting method of providing for a wide variation in driving speed and power consists in using *two motors in conjunction with epicyclic gearing*. For maximum speed and output, both motors are operated at full speed; they then assist each other in driving the load, the epicyclic gear serving merely as a mechanical coupling between the two motors and the load, with the important advantage that it does not place any constraint on the motors should they not be running at the same speeds. In order to drive at reduced speed and power, one of the motors is disconnected from the supply; the other remains in circuit, and, the epicyclic gear being now operative, the load is driven at a reduced speed. One of the applications of this system is in driving a to-and-fro aerial ropeway, the lower power and speed being used near the end of the run in order to facilitate accurate stopping of the car or bucket.* Another application is in the accurate 'landing' of lift or elevator cars. By varying the ratio of the horse-powers of the two motors, and the ratio of the gearing between them, the principle explained may be applied to a variety of conditions.

Friction clutches are used to enable a motor to 'pick up' its load gradually, or to prevent excessive mechanical shock being

* See *Zeits. des Vereins. deutsch. Ing.*, Vol. 71, p. 1754.

imposed upon the motor during normal running. The slip of a belt may serve both of these purposes, but not with any marked degree of uniformity and reliability, and only at the cost of rapid wear on the belt. Where progressive coupling and a limitation of torque are required, it is best to use a friction clutch designed specifically for this purpose. The clutch may be of any of the well-known mechanical types, *e.g.* cone clutch, plate clutch, centrifugal clutch with pivoted pads gripping the inner circumference of a cylindrical shell. Alternatively, it may be magnetically operated. In this case, an electromagnet, rotating with the clutch or stationary within it, according to the details of design, is used to pull a spring-borne or sliding part on the driven shaft into contact with a corresponding part on the driving shaft; a friction lining is usual in small clutches, but a non-magnetic metal friction block is used in certain high-power clutches.* The advantages of magnetic clutches include elimination of operating mechanism, saving of space, and easy operation by switching from any distance.

Reversal of the direction of driving can generally be effected more conveniently and satisfactorily by a *reversing motor* than by any form of mechanical reversing gear. Where a short-stroke reciprocating motion is required, as in slotting machines and jig conveyors, the reciprocating part may be driven from a continuously rotating motor through a crank and connecting rod. In planing machines, the bed may be reversed by means of belt-shifting gear which brings an open-belt and a crossed-belt alternately into action. The slip which occurs at the oncoming belt leads to rapid scorching of the latter and the reversal is neither rapid nor accurately timed. By using adjustable 'dogs' or triggers, tripped by the bed or other part which is to be reversed, to actuate reversing switches in the circuit of a motor directly coupled or rigidly geared to the part concerned, prompt and accurate reversal can be obtained. The kinetic energy of the moving parts can be absorbed rapidly by electrodynamic braking, this energy being either dissipated as heat in a special braking resistance, or returned to the supply mains in the

* Forster magnetic clutches, as used between water turbines and generators, to allow the latter to be run light as synchronous motors for P.F. correction, are of the double-cone all-metal type. A clutch of this type to transmit 17 000 H.P. at 500 r.p.m. weighs less than 8 tons, and absorbs about $2\frac{1}{2}$ kW D.C. for excitation. (See also *El. Rev.*, Vol. 100, p. 1039.)

case of regenerative braking (§ 715). A reversible motor eliminates the inertia of the mechanical reversing gear otherwise required and is capable of reversing at a speed which could be equalled by no mechanical device except, perhaps, by a costly hydraulic transmission. Striking examples of reversible motors are to be found in electrically driven rolling mills.

In any reversing drive the moment of inertia of the moving parts should be kept as low as possible, in order to reduce the mechanical shock of reversal and keep down the braking and accelerating currents. The moment of inertia of the load itself is presumably a fixed quantity in any particular case, but the moment of inertia of the motor itself can be reduced by using an armature or rotor of small diameter. In other words, a motor with a small number of poles and a long armature is preferable to a multipolar machine with a shorter armature of greater radius of gyration.

The object of *flywheels*, as applied to electric motors, is to equalise the demand on the supply mains by storing energy in the flywheel during periods of light load and utilising some of this energy to assist the motor during periods of heavy load. In order that this action may be possible, the flywheel must be able to accelerate during the periods of light load, and slow down during the periods of heavy load. If the flywheel is mounted on or connected rigidly to the shaft of the driving motor, the speed of the latter must vary with the load, otherwise the flywheel can render no assistance. In some cases, however, the main motor may be a constant-speed machine, the flywheel being driven by an auxiliary motor which is subjected to regenerative braking (§ 715) during periods of peak load; the flywheel then drives the auxiliary machine as a generator assisting the mains in supplying the principal motor. In any case, flywheel storage can only be used to equalise the demand when the motor driving the flywheel can be varied in speed either by its inherent characteristics or by artificial means (*e.g.* automatic variation of slip-resistance in the case of an induction motor). Where it is properly applied a flywheel makes possible the use of a smaller, cheaper motor than would otherwise be needed for a fluctuating load. On the other hand, a heavy flywheel is expensive in itself and as regards the bearings required for its support. There is appreciable loss of energy by friction and windage, particularly in the case of large, high-speed flywheels;

and most of the energy in the flywheel is lost every time the is stopped. For these reasons, it is difficult to use fly economically with motors which operate very intermittently.

Though a synchronous or synchronous-induction motor is definitely a constant-speed machine and therefore incapable of benefiting from the use of a flywheel to equalise peak loads, a fly-wheel may be used to reduce the liability to hunting or pulling out of synchronism when driving air compressors or other loads having large cyclic irregularity, *i.e.* varying widely during each revolution of the driven machine. For a full treatment of flywheel storage, see §§ 828, 829.

752. Choice of Motor Horse-Power.—The bases of rating for various types of electric motors are explained in § 670, from which it will be seen what is meant by the 'horse-power' of an electric motor. For maximum economy, the horse-power of the motor selected for any drive should not be greater than is required to enable the driven machine, or machines, to be operated under the desired conditions. It is, however, better to install too large a motor, rather than risk overloading it or, alternatively, restrict the output of the driven machine by using a motor of inadequate horse-power.

If an unnecessarily powerful machine be used it will operate considerably below its maximum efficiency and power factor; for example, a 50 H.P. induction motor of 90 % efficiency and 0.88 power factor on full-load has an efficiency of $87\frac{1}{2}$ % and a P.F. of 0.82 at 60 % load. On the other hand, too small a motor will either fail to keep the driven machine up to its rated output or it will be dangerously overheated by sustained overload. In the case of A.C. motors which have a definite pull-out torque this must be considered, particularly where individual driving is employed; a group motor will usually deal with any peak load which may arise on particular machines in the group. The pull-out or stalling torque of an induction motor is usually between 2 and $2\frac{1}{2}$ times the normal full-load torque; and the rated H.P. of a motor of this type is generally at least two-thirds of the maximum H.P. demanded by peak loads.

It is often asserted that there is, in general, no need to 'over-motor' machines because the overload capacity of modern electric motors is as high as that of the machines which they drive. This, as a general statement, is true, but the makers of the driven

machinery sometimes state too low a value for the power *normally* required to drive their machines, with the result that a motor selected on this basis would be *permanently* overloaded. The remedy is, of course, to insist upon witnessing measurements of the power absorbed by a motor driving the machines in question under service conditions. A certain addition, say 10 or 15 %, should be added to the observed figure to allow for contingencies, including the fact that the demonstration machine would doubtless be specially tuned for the occasion.

In some cases, as, for instance, in hoisting or pumping, it is a simple matter to calculate the power theoretically required; this value, divided by the mechanical efficiency of the driven machine, gives a value for the motor-H.P. to which 10 or 20 % may be added at discretion to cover contingencies. A much safer method is, of course, to drive the machine temporarily by a motor which is known to be of ample power, meanwhile recording the power input by means of a graphic wattmeter. Ordinates from the chart so obtained are multiplied by the efficiency of the motor, corresponding to each value of kW-input, in order to determine the mechanical power absorbed by the driven machine.

For example, a 20 H.P. motor may be used temporarily to drive a machine which is believed to require about 10 H.P. From the wattmeter chart it is found that the input to the motor is 11.2 kW when the driven machine is working under the desired conditions. From a curve previously prepared, showing the efficiency of the motor at various values of kW-input,* it may be found that the efficiency of the motor is 80 % at 11.2 kW input. The motor output is then 0.8×11.2 or 8.95 kW, which equals $8.95 / 0.746$ or 12 H.P. Hence the power actually required by the driven machine under the conditions of test is 12 H.P.

Where a D.C. motor is used for the above test, a recording ammeter may be used instead of a wattmeter, but with an A.C. machine it is simpler to use a wattmeter, because this automatically takes account of the power factor of the motor.

If the driven machine requires a continually varying input, the root-mean-square (R.M.S.) value of the latter should be determined by: (a) squaring the ordinates of a recording ammeter chart and plotting the results as an I^2 curve; (b) determining the mean ordinate of this new curve and extracting its square root, thus obtaining the R.M.S. current value which determines the heating

* This special curve can be easily calculated from the efficiency-output curve if the latter is the form initially available.

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of the motor. The power corresponding to this current, allowing for P.F. in the case of A.C. machines, is the R.M.S. power which determines the heating of the motor, but the latter must also be capable of carrying the peak loads shown by the recording ammeter chart, and if there are rest periods in the cycle the problem becomes very complicated (*see* § 670). If sufficient fluctuation of speed is permissible to make the use of a flywheel economical this will enable a smaller motor to be used than would otherwise be required. Alternatively, the driven machine may be made one of a group driven by a motor which is capable of carrying the peak loads of the individual machines whilst normally operating at a reasonable load factor.

A group-driving motor must be capable of operating continuously at the mean load of the group and, at the same time, of supplying the peak demands of individual machines. Usually, the diversity factor of the group and the overload capacity of the motor are sufficient to prevent any trouble arising from coincidence of peak loads on two or more of the driven machines, but if the peak requirements of the latter are very severe it may be advisable to install an electrically operated signal which will warn other operators in the group that one machine is 'on peak.' An application of this principle to the avoidance of simultaneously starting of heavy loads is mentioned in § 744.

In some instances, where the power required for a group-drive is much greater during certain periods than at other times, two motors may be coupled to the lineshaft through friction clutches, one or both motors being used according to the load to be carried. This arrangement does not apply where the load is fluctuating continually over a wide range, but where the load is known to be below a certain value during a definite period.

The H.P. of the engine used in an existing mechanically-driven plant is of little assistance in determining the H.P. of the motors required to drive the plant electrically. Even if no changes are made in the machinery driven, the substitution of the electric drive should eliminate much of the frictional loss associated with mechanical driving; on the other hand, the H.P. of an engine driving the whole plant may be only 60 or 70 % of the aggregate H.P. of the group and individual electric motors in the 'electrified' plant (§ 748).

Where a motor is to be operated for considerable periods at

much below its maximum speed, its temperature rise at stated output is considerably increased by the fact that a higher torque, and therefore a heavier current, is required to develop the same power at the lower speed. Even when working with the same current at both speeds, the heating is greater at the lower speed because of the smaller cooling effect of the decreased windage. Similarly, a motor which is used for regenerative braking is subject to continued heating during at least a part of the time when it would otherwise be electrically idle and therefore cooling. For either or both of these reasons it may be necessary to use a larger motor than would otherwise be required.

The importance of determining the actual power requirements of the load is particularly great where A.C. motors are to be substituted for D.C. machines as a consequence of charge-over from D.C. to A.C. supply. The natural tendency might be to install A.C. machines of the horse-power stated on the name-plates of the D.C. machines, but it should be remembered that: (a) the D.C. machines may be unnecessarily large, in which case smaller A.C. motors would operate at higher efficiency and power factor, besides reducing the capital cost of the conversion; (b) on the other hand, the overload capacity of many existing D.C. motors is considerably higher than that of new A.C. motors, and if advantage has hitherto been taken of the high overload capacity of the older machines it will be necessary to replace the latter by A.C. motors of higher rated horse-power. Measurements of the actual power requirements are the only basis on which technically satisfactory results can be guaranteed. Even so, it is advisable to ascertain, in case (a), whether the consumer will be satisfied with the smaller motor which will give him better service, or whether he will insist on having a motor of the same horse-power as before. In case (b) the supply authority would be well advised to install a larger motor if necessary to ensure satisfactory service; the consumer should not be penalised for the fact that the rating of his old motors are on a more conservative basis than that of the new machines. If his old 5 H.P. motor has been running satisfactorily at 8 H.P. he should be given an 8 H.P. motor in its stead or, if it can be arranged, a cash indemnity leaving him to buy new motors on his own responsibility.

753. Selection of Electrical Type of Motor.—The general aim should be to use that type of motor which can be started most easily and used with maximum overall efficiency in the service

concerned. As explained in § 749, the motor should have as nearly as possible the same torque-speed characteristics as the load. Four main types of characteristics may be distinguished, *viz.* : (1) Series; (2) shunt; (3) compound; and (4) synchronous. Characteristics of the first three types may be obtained from D.C. and A.C. machines, but the synchronous motor is essentially an A.C. machine.

Motors with a *series characteristic* are distinguished by their high-starting torque and by the fact that their speed decreases as the load increases. The prototype of this class is the D.C. series motor. The A.C. series commutator motor has the same characteristics. From the point of view of choosing a suitable motor, it is convenient to say that a load has series characteristics when it could be driven satisfactorily by a D.C. series-wound motor; and that a motor has series characteristics when its torque-speed characteristics are similar to those of the D.C. series motor, regardless of whether the motor considered is actually series-wound. Similarly, a motor may be said to have shunt characteristics or compound characteristics when its torque-speed curve resembles that of the D.C. shunt- or compound-wound motor, regardless of whether the actual motor is for D.C. or A.C., and whether it has or has not shunt or compound connections.

Motors with a *shunt characteristic* are distinguished by a close approximation to constant speed on variable load, the actual speed decreasing slightly as the load increases. Motors with *compound characteristics* may correspond to the D.C. *cumulatively*-compounded motor, in which the starting torque is higher than that of the shunt motor but less than that of the series motor, while the decrease of speed with increasing load is also greater than that of the shunt motor but less than that of the series motor; or they may correspond to the D.C. *differentially*-compounded motor in which the effect of the compounding is to maintain practically constant speed at all loads. Motors with *synchronous characteristics* run at an absolutely constant speed determined solely by the number of poles in the motor and the frequency of the A.C. supply.

If a motor has to be started frequently on load, it is essential to choose a type which can be started easily under such conditions, but where a machine is to run for hours or days at a time easy starting becomes a secondary consideration. For example, the D.C. series-wound motor is by far the best type for traction and

similar service; while, before the self-starting synchronous motor had reached its present perfection, the inconvenience of starting the plain synchronous motor was rightly considered of minor importance compared with the high P.F. of the machine where long-hour service was concerned and arrangements could be made to start the motor light.

The choice between D.C. and A.C. motors is determined partly by considerations of weight and cost, but mainly by the operating characteristics of the alternative types of machines. There is no marked difference between the efficiencies of D.C. motors and polyphase A.C. motors, the difference seldom exceeding 2 or 3 % in machines up to 50 H.P. (less in larger machines), and being in favour of one type or the other according to the details of the design.* Up to 5 or 10 H.P. polyphase induction motors may be from 20 to 30 % lighter than D.C. shunt motors for the same power, voltage and speed. For an output of about 50 H.P. the polyphase induction motor may be about 15 to 20 % lighter than a D.C. shunt motor of the same voltage and speed; but it must be remembered that A.C. induction motors can easily be built for much higher voltages than D.C. motors, thus effecting a further saving of weight. On the other hand, the speeds of induction motors are determined by the number of poles and the frequency of supply (about 1 450 r.p.m. for a 4-pole machine, 725 r.p.m. for 8 poles on 50-cycle supply, and so on), whereas a D.C. motor is subject to no such limitation, and may therefore be chosen for the exact speed required by a particular drive. The fact that induction motors have no commutator is a consideration of some importance when the machines are to be used in explosive atmospheres or otherwise unfavourable positions. The risk of an explosion being caused by sparking at a slip-ring is practically as great as that of its being caused by sparking on a commutator and, in either case, a flame- and explosion-proof casing prevents the explosion from spreading. From the point of view of explosion risk there is little to choose between commutator and slip-ring, but the squirrel-cage rotor gives absolute security. As regards maintenance, however, under conditions which are dangerous or detrimental the commutator is at a disadvantage compared with the slip-ring.

* The same 'carcase' can generally be used for several different speeds and outputs by using different windings and connections. This effects a reduction in the costs of manufacture, but the efficiency of some of the machines is lower than it would be if each machine were designed solely for its particular output and speed.

As regards load-speed characteristics, the equivalence between D.C. and A.C. motors is roughly as follows: (1) The A.C. induction motor with short-circuited rotor (whether squirrel-cage or phase-wound) has a load-speed curve resembling that of the D.C. shunt-wound motor; with the important distinction that the speed of the D.C. shunt motor can be set to any desired value, or varied continuously within a wide range, by field control. (2) The A.C. synchronous motor is inherently a constant-speed machine. The nearest approach to it in D.C. practice is the level-compound (differentially-compounded) motor. (3) The characteristics of the D.C. series motor are practically identical with those of the single-phase A.C. series motor; and the repulsion motor has similar characteristics, with the advantage that it does not race on light load. (4) The load-speed characteristics of the D.C. cumulatively compounded motor can be duplicated by the A.C. induction motor with a slip-regulator. (5) The characteristics of any type of D.C. motor can be obtained from one or other of the many special types of A.C. commutator motors, but most of these machines are considerably more complicated and expensive than D.C. motors.

The characteristics and control of individual types of motors are discussed in Chaps. 28 and 29, where also the applications of the various motors and methods of control are considered. The following notes will be found useful as a guide to the *selection of motors to meet stated requirements*, e.g. constant or variable speed, high starting torque, fluctuating load, rapid reversibility, high power factor, high efficiency, and so on.

General Considerations.—The motor characteristics in starting and on load must correspond as closely as possible with those of the load, particularly where a motor is used to drive a single machine. Unsuitable starting characteristics may sometimes be overcome by starting the motor light and then connecting it to its load by friction clutch, belt, or gear box. Unsuitable characteristics on load are generally fatal. The use of too large a motor means idle capital investment, loss of efficiency, and (in A.C. working) low P.F. A.C. motors are often built to yield maximum P.F. and efficiency at 75 % rated output, and it is always advisable to see that the P.F. and efficiency are, at any rate, not much lower on 75 % than on full rated load.

Where its operating characteristics are acceptable, the A.C. squirrel-cage induction motor should be adopted as being the simplest and most rugged electric motor, requiring a minimum of attention.

No motor which is liable to race (e.g. a D.C. series motor) may be used where the load can ever become low enough to permit a dangerous rise of speed. For group-driving a motor of constant or nearly constant speed is required.

Constant Speed.—The synchronous A.C. motor is easily the best type as regards constancy of speed; its speed is determined absolutely by the frequency of the A.C.

supply (§ 679), which is held constant within very close limits by every public supply station. It may be noted, however, that there is appreciable risk of the alternator speed, and therefore the supply frequency, being allowed to vary in private power plant, particularly when there is only one alternator in service.

For many purposes, the D.C. shunt motor (§ 675) may be regarded as a substantially constant-speed machine. The same is true of the A.C. induction motor (§ 681) when this is operated with a short-circuited rotor of low resistance. An A.C. induction motor with a rotor of high resistance (whether internal or external) is definitely a varying-speed machine.

A level-compounded D.C. motor (differentially compounded § 677) may be used where the small decrease in speed of a shunt motor with increasing load is inadmissible.

Motors which may be subjected to low voltage of supply, due to line-drop or other causes, should be of the synchronous or synchronous-induction types (§§ 679, 696) in order that their speed may be maintained. This is particularly desirable when driving centrifugal pumps or other machines, the output of which is seriously affected by a drop in speed. Many such machines are used in outlying situations for which A.C. transmission is specially suitable, and where the high P.F. of the synchronous motor reduces transmission losses (compared with those arising where A.C. at lower than unity P.F. is concerned).

Adjustable Speed.—When it is desired to adjust or ‘set’ the speed to any particular value within a prescribed range, regardless of load variations, the motor itself must have constant speed characteristics, but the actual value of the constant speed must be adjustable. A shunt-wound D.C. motor (§ 675) with field control will meet most requirements, but, if a very wide range of speed adjustment is required (say, greater than 5:1), a D.C. motor may be used with separate excitation of the field and adjustable armature voltage. In the latter case, rheostatic adjustment of the field current may provide part of the speed adjustment, as in an ordinary shunt-wound machine; or the speed adjustment may be obtained solely by varying the armature voltage. Either multi-voltage supply (§ 716) may be used, giving a series of definite speeds between which adjustment must be obtained by field control, or the field may be kept constant and provision made for varying the armature voltage continuously and *independently of the load*. This demands the use of a variable-voltage D.C. generator, as in the Ward-Leonard system of control (§ 716); adjustment of the armature voltage by series resistance would not only be inefficient but would also result in a variable-speed drive, the pressure drop in the regulating resistance increasing with the load, and thus reducing the voltage applied to the armature.

Continuously adjustable, ‘set’ speeds (as distinct from multi-speed driving) can be obtained from A.C. motors by the use of brush-shifting A.C. commutator motors with shunt characteristics (§ 706). Another method is to use frequency changers in conjunction with induction motors, but this is generally expensive. Wide and continuous control of speed can be obtained with various types of A.C. commutator motors, but D.C. shunt and compound motors are still generally considered to be the simplest, cheapest and most reliable for such service. In point of range of speed variation, certain A.C. commutator motors offer the advantage of speed control from zero to far above synchronous speed in either direction by brush displacement alone; *see also* § 698.

Multi-Speed Driving.—Where it is desired (or sufficient) to drive a machine at one or other of several definite speeds, a pole-changing squirrel-cage or wound-rotor induction motor (§ 686) may be used. The speed of the motor is inversely proportional to the number of poles, which can only be varied satisfactorily in some simple

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ratio, e.g. 2 : 1. One example of the application of such coarse control is to be found in the driving of the ventilating fan for a new colliery, where it may be sufficient to run the fan at half-speed for a year or two until the underground workings have been extended sufficiently to require the full output of the fan. Belt-shifting or change-speed gears in conjunction with a constant speed motor offer another means of obtaining a few definite speeds; and series-parallel switching (§ 718) or multi-voltage supply (§ 716) enable D.C. motors to be operated efficiently at any one of a few definite speeds.

Multi-speed control of a wound-rotor induction motor can be obtained by means of a step-by-step rheostat in the rotor circuit, but the regulation losses thus involved reduce the overall efficiency; and the speed corresponding to each position of the rheostat varies if the load changes.

Where two- or three-speed motors of very low speed are required, two motors in cascade may be employed (§§ 694, 727); such sets can be arranged for operation at variable speed in addition to the fixed speeds.

Speed varying with Load (Variable-Speed driving).—The D.C. series-wound motor (§ 676) is usually the best machine for this class of service, provided that there is no possibility of the load being reduced to such an extent that the motor speed becomes dangerously high. Alternatively, A.C. commutator motors with series characteristics (§§ 700, 708) may be used.

If it is desired that the variation of speed with load should be greater than that of a D.C. shunt motor but less than that of a D.C. series motor, a cumulative-compound D.C. motor may be used (§ 677).

The speed of a wound-rotor induction motor may be made to decrease considerably, with increasing load, by the insertion of slip-regulating resistance in the rotor circuit; this arrangement is useful where it is desired to employ flywheel storage, but the efficiency suffers owing to the I^2R losses in the slip-regulating resistance. An induction motor with a high-resistance squirrel-cage winding on the rotor also decreases automatically in speed as the load increases. In this case, however, the 'slip-resistance' is an integral part of the rotor winding, hence the considerable droop in the load-speed characteristic and the rapid increase of I^2R losses in the rotor cannot be avoided (as they can be by short-circuiting an external rheostat); also, a larger motor is required for given output when the regulating or slip-resistance losses occur in the rotor winding itself than when the greater part of these losses occur in an external resistance.

The plain repulsion motor has a load-speed characteristic resembling that of a D.C. series motor, and its speed can be altered by means of a multi-tapping transformer, changing the applied voltage; or, within a limited range, by brush-shifting (§ 733).

High-Starting Torque.—The D.C. series-wound motor (§ 676), or an A.C. commutator motor with series characteristics (§§ 700, 708), may be used if there is no objection to the speed varying widely with the load. In other cases, the D.C. cumulative-compound motor (§ 677) may be employed, the starting torque, and also the variation of speed with load, increasing with the relative strength of the series-field, compared with the shunt-field ampere-turns.

If the load is ever so light that a series motor would reach a dangerous speed, a cumulatively-compounded D.C. motor should be used. An A.C. induction motor develops relatively high starting torque if the resistance of the rotor winding be high, or if external resistance be connected in series with the rotor winding during starting; the latter solution is preferable from the standpoint of efficiency (§ 681), but the simplicity of the self-contained high-resistance rotor may justify its use in small machines. Wherever an induction motor has to be started frequently, a slip-ring

machine with external rotor-resistance should be employed in preference to a squirrel-cage motor, because: (a) the starting current is lower for a given starting torque; (b) the losses in an external resistance do not heat up the motor. For both of these reasons, the slip-ring motor may be smaller than the squirrel-cage machine.

Fluctuating Loads and Reversible Driving.—The most economical method of driving a fluctuating load is by means of a motor with series or compound characteristics, i.e. by a machine, such as a D.C. series or compound motor or an A.C. induction motor with slip regulation. The speed of such motors drops or tends to drop with increasing load; the actual speed drop may be decreased by the use of a flywheel, but unless the motor itself has a drooping load-speed curve it cannot allow the flywheel to deal with the peak load.

Where the peaks of a fluctuating load would necessitate a motor of considerably higher H.P. than the average load, a flywheel may be used if the speed-load curve of the motor drops sufficiently to enable advantage to be taken of flywheel storage. If an induction motor is used without a slip-regulator, little assistance can be derived from a flywheel; in such a case, the use of a compensated induction motor (§ 688) may be advisable, the higher overload capacity of the compensated machine permitting the use of a lower rated H.P. than would otherwise be required.

For reversible driving, the moment of inertia of the motor itself should be as small as possible, a long armature of small diameter being preferable to a short one of larger diameter. A D.C. cumulatively-compounded motor combines easy reversibility with high starting torque. For very severe reversing service, such as colliery winding and rolling mill drive, a D.C. motor in conjunction with the Ward-Leonard system of control (§ 716) enables advantage to be taken of flywheel storage, the flywheel capacity being in the electrically-reversible D.C. generator and not in the driving motor which reverses its direction of rotation.

Flywheel Storage.—If it is desired to use a flywheel to carry peak loads, equalising the demand on the supply mains and making possible the use of a motor of lower H.P. than would otherwise be needed, the motor must decrease in speed, with increasing load, sufficiently to enable the flywheel to give up a useful proportion of its stored kinetic energy. The smaller the decrease in speed the heavier the flywheel needed to obtain a given output of energy, the stored energy at any moment being proportional to the square of the speed of the flywheel. The types of motors usually employed with flywheels are the cumulative-compound D.C. motor (§ 677), and the A.C. induction motor with slip-regulator (§§ 725, 728); the former has characteristics giving the desired decrease of speed without regulating losses, but the slip-regulator of the induction motor involves I^2R losses during the period for which the regulating resistance is inserted in the rotor circuit.

It is useless to fit a flywheel to a synchronous motor, and of very little use to fit one to a shunt-wound D.C. motor, for the speed of the former is constant, and the speed of the shunt motor falls only a few per cent. from zero to full-load—not enough to permit a flywheel of moderate weight to give out any useful amount of energy. On the other hand, the speed of a series D.C. motor decreases very considerably with load; indeed, the speed variation is too great for most kinds of work to which flywheel storage is usefully applicable, and during periods of light load the speed is apt to become dangerously high. The cumulatively compound-wound motor represents a compromise between these two extremes. By adjusting the degree of compounding the speed can be made to decrease automatically on load, by any desired amount, so that flywheel storage can be utilised very effectively. A standard squirrel-cage motor has much the same load-speed characteristics as a D.C. shunt motor, and therefore benefits little from the provision of a flywheel. A slip-ring motor with variable rotor resistance (preferably inserted automatically on the occurrence of overload) may be

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made to slow down considerably on load, so that good use may again be made of flywheel storage. It must, of course, be understood that in any case the provision of a flywheel does no more than to equalise the demand in the supply mains; it does not reduce the total energy consumption except perhaps by saving something in efficiency by equalising the load. Its main effect is to permit the use of a small D.C. compound or A.C. slip-ring induction motor with flywheel instead of the larger and costlier machine which would be required without flywheel storage.

Where a flywheel is employed, its effect upon the starting conditions must be considered. The shorter the starting period, *i.e.* the higher the rate of acceleration, the higher the starting torque; and, for any given rate of acceleration, the starting torque increases with the inertia of the load, including the flywheel. As the primary object in using a flywheel is to prevent abnormal torque being demanded from the motor, the starting period should be prolonged. This will necessitate liberal design in the starting gear.

High Power Factor.—In the interests of high power factor synchronous motors (§ 679) or synchronous-asynchronous (§ 696) motors should be used wherever possible. By over-excitation of a synchronous motor, the average power factor of a mixed load can be materially improved (§ 160, Vol. 1), while still using the synchronous machine for mechanical driving. Compensated induction motors (§ 688) and commutator motors (§ 699) are also preferable to ordinary induction motors, from the standpoint of high power factor.

The precaution most commonly needed, in order to maintain a satisfactory value of power factor, is to avoid the use of ordinary induction motors operating at much below 75 or 70 % of their rated load (§ 681). This is mainly a matter of determining the actual power requirements of the load before selecting the motor. Where the load is very irregular, a flywheel may be provided to relieve the motor of the peak loads and thus make possible the use of a smaller machine, operating at a higher percentage of its rating, than would otherwise be possible. Where an induction motor is concerned, however, a special slip-regulator (§§ 725, 728) must be provided, otherwise the speed of the flywheel will remain so nearly constant that little assistance will be given to the motor; the rated H.P. of the latter must then be high, and the average P.F. correspondingly low on variable load.

It is becoming increasingly common to embody in electricity supply tariffs a penalty for low P.F., or a bonus for high P.F. (§ 274, Vol. 1); this gives the consumer an incentive to study the P.F. of his demand and may lead him to incur expenditure on phase-compensating equipment (§ 160, Vol. 1). Apart from possible savings on the electricity bill, the only advantage the consumer gains from raising the P.F. of his load is that the voltage drop and energy loss (I^2R) in his distribution cables are a minimum at unity P.F. If he employs some motors at a leading P.F., to compensate for others at a lagging P.F., the voltage drop and I^2R loss in the circuits carrying leading current will be the same as for an equal current at a numerically equal lagging P.F. The only substantial advantage of P.F. correction from the consumer's point of view lies in the saving effected by qualifying for a lower supply tariff.

It is particularly desirable to use synchronous or synchronous-induction motors for low-speed A.C. drives, in preference to induction motors, because the P.F. of the latter is relatively low in low-speed machines (§ 681).

High Efficiency.—On general principles, high efficiency is always desirable, but in most cases higher efficiency involves higher capital expenditure and it remains to be decided whether it is better to economise on investment or on running costs. Efficiency in operation is more important, and more can be spent profitably in obtaining it in steel mills, cement works and other concerns, where power represents a relatively large proportion of the total cost of the product, than where the cost of

power is low compared with that of labour, material and standing charges on costly machines. The more energy (kWh) consumed and the higher the cost per unit, the better it pays to install high-efficiency motors; while the smaller the consumption, the more important is capital economy.

As an example, suppose that the choice lies between two 12 H.P. motors, one costing £25, the other £20; the efficiency of the more expensive machine being 87% at three-fourths of full-load, whereas that of the cheaper machine is only 84%. If the motors be used 2 000 hours per annum at this average load,* the more efficient machine will consume $(9/0.87) \times 0.746 \times 2\,000$ or 1 542 kWh, while the less efficient machine consumes $(9/0.84) \times 0.746 \times 2\,000$ or 1 600 kWh (approx.). At 1½d. per kWh, the saving effected by the more efficient motor is $(1\,600 - 1\,542) \times 1\frac{1}{2}$ or 87d. per annum. This represents a return of $100 \times 87 / (5 \times 240)$ or 7¼% on the £5 higher cost of the more efficient machine. If energy cost 3d. per kWh, the saving effected by the more efficient motor would be twice as great, and so on.

Apart from the direct saving effected by higher efficiency, owing to reduction in the energy consumption, the more efficient motor is likely to run at a lower temperature and therefore to be more durable; also, it is probably of better design and manufacture throughout. In many instances these considerations will be of greater importance than the possible saving on energy consumption, but it is always worth while to investigate the question of relative efficiencies, particularly in the case of small motors, because the differences between individual makes are often greater in machines of low horse-power; also, such motors are often supplied at a relatively high price per kWh. Though a certain amount of reticence is often displayed with regard to the efficiency of small motors, it is a figure which the purchaser is perfectly entitled to demand.

Though restrictions in this respect tend to become less onerous as the capacity of supply stations and networks increases, it is possible that the choice of a motor for any particular service may be affected by the regulations of the supply authority.

754. Considerations of Supply; Current Required by Motors.—Except in so far as there may be a choice of systems available, the form of the public supply of electricity is beyond the control of the consumer, who may, however, transform or convert the primary supply to any form more suitable to his requirements (see Chap. 17, Vol. 2). For example, the fact that A.C. supply is alone available from the mains need not preclude the use of D.C. motors if the latter are preferable to A.C. machines in any particular case; a rotary converter, a motor-generator, or a mercury rectifier may be installed in the consumer's substation, the relative merits of the several equipments being as noted in § 425, Vol. 2.

* In order to make the comparison strictly accurate, the energy consumption of the two machines should be calculated by taking the annual load curve in conjunction with the actual efficiencies of the machines at each load. This is not difficult in the case of motors on a definite cyclic duty, but, in general, such a refinement of computation is neither necessary nor practicable.

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In the interests of economical wiring and cheap supply (price per kWh), it is inadvisable to connect any but the smallest motors to the lighting supply at 100-250 V; indeed, the supply authority usually allows only domestic motors up to $\frac{1}{8}$ or $\frac{1}{4}$ H.P. to be connected to the lighting mains. The majority of industrial motors are connected across the outers of a 3-wire D.C. supply or to 3-phase A.C. mains at a pressure of from 400 to 500 V (§ 23, Vol. 1); sometimes D.C. supply at 500-600 V is available, usually from a traction network. A.C. supply to large industrial consumers is usually at high pressure (3 300-11 000 V); this is generally reduced to 416 / 240 V by static transformers for motors up to 50 H.P. or so, but larger machines may be supplied at high tension.

Where outlying loads are concerned, *e.g.* pumps, mine fans, ploughing motors, etc., economy in distribution demands the use of high pressure right up to the motors concerned; the alternatives are then either to use a step-down transformer and low-voltage motors, this being desirable in field service (agriculture, excavators, etc.) and other cases where motors have to be operated out of doors or by unskilled labour; or a high-voltage motor may be used if the machine is of not less than 50 H.P. or so, and operates indoors under the care of a skilled man.

Current required by Motors.—The current in amperes required by any D.C. motor = $(\text{B.H.P.} \times 746) / (\text{Volts} \times \text{Efficiency})$, the efficiency being expressed as a decimal. The pressure may be whatever the designer makes it, according to the circuit to which the motor is to be connected. In the case of single-phase alternating current the figure arrived at above must be divided by the power-factor to give the virtual amperes, and in the case of 3-phase current the divisor is $1.73 \times$ the power-factor.

EXAMPLE.—Consider the case of a 10 B.H.P. motor. If it is designed for 220 V direct current, with an efficiency of 85 %, the current will be 40 A. The electrical input of the motor will then be 220×40 W or 8.8 kW. If the supply is single-phase at the same pressure, the efficiency 75 %, and the P.F. 0.8, the current will be $(10 \times 746) / (220 \times 0.75 \times 0.8) = 56\frac{1}{2}$ A (virtual). This larger current must be carried by the wires leading to the motor, but being out of phase with the pressure it does not all come into account in the power taken. The electrical input of the motor will then be $220 \times 56\frac{1}{2} = 12.4$ kVA (kilovolt-amperes), but it will only be $12.4 \times 0.8 = 9.9$ true kW. If the supply is 3-phase at the same pressure, with a motor efficiency of 80 % and P.F. of 0.85, the current will be $(10 \times 746) / (220 \times 0.8 \times 0.85 \times 1.73) = 28.8$ A (virtual) in each phase. The electrical input of the motor will then be $220 \times 28.8 \times 0.85 \times 1.73 = 9.3$ true kW.

The calculations illustrated by the preceding example should be made whenever the efficiency and power factor of the motor are

known. For purposes of general estimating, use may be made of Table 136 which is referred to a pressure of 100 V for ease in calculation and based upon typical values of efficiency and power factor. The use of this table is illustrated by the following example:—

EXAMPLE.—What is the full-load current required by a 50 H.P. single-phase motor supplied at 440 V?

From Table 136, the current required by a 3-phase motor at 100 V is about 270 A; therefore, at 440 V it is about $270 \times 100 / 440$ or 61.3 A. The current taken by a single-phase motor would be about twice that required by a 3-phase motor (*see* footnote to Table 136), *i.e.* in this case 2×61.3 or, say, 123 A.

In many districts the supply authority imposes regulations concerning the types of motors which may be used and the conditions under which they must be operated.

For example, it may be stipulated that:—

(1) D.C. motors may be connected across the lighting mains for domestic power purposes, but only across the outers of a 3-wire system for industrial purposes.

(2) Single-phase motors not exceeding 2 H.P. may be installed; all A.C. motors above this size must be 3-phase.

(3) Squirrel-cage induction motors up to 5 H.P. may be switched directly on to the line.

(4) Squirrel-cage motors are permissible up to 30 H.P. provided that they are started on light load and by an auto-transformer or other device which will limit the starting current to a value not exceeding twice full-load current.

(5) All induction motors exceeding 5 H.P. starting against load must be provided with slip-rings, a wound rotor, and such starting resistances that the current does not exceed full-load value at any step of the starter.

(6) If the average P.F. of the consumer's motor load be less than 0.8, the supply tariff shall be subject to certain increases.

Restrictions of this type and degree are still enforced by many supply authorities in this country. Ultimately, low P.F. will probably be penalised by every supplier of electricity (§ 274, Vol. 1), but the tendency is to relax the restrictions upon the use of squirrel-cage motors with short-circuited rotors; in America it is common for machines of this type up to 30 or 50 H.P. to be started by switching straight on to the mains.

755. Small Power Applications.—Small electric motors, often of fractional horse-power, are used extensively to drive appliances in domestic service, hotels and offices, as well as for portable tools in industrial plants.

Motors from $\frac{1}{16}$ H.P. upwards are listed for a variety of domestic uses, such as driving sewing machines, knife or boot cleaners, etc. They run for the most part at very high speeds—2 000 r.p.m. or thereabouts for direct current, and a little lower for alternating

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TABLE 136.—*Approximate Full-Load Current taken by Electric Motors at 100 V.*

NOTE.—This table should be used only for purposes of general estimating. Wherever possible, the current consumption should be calculated by using the actual values of P.F. and efficiency for the machine concerned.

Current consumption at E volts = value from table $\times \frac{100}{E}$.

Current for single-phase motors = $2 \times$ current for 3-phase motors.*

Current for 2-phase motors = $0.9 \times$ current for 3-phase motors.*

Horse-Power.	Direct Current. Amps. at 100 V.	3-Phase A.C. Amps. at 100 V.
1	11.0	8.0
2	19.5	14.5
3	28.5	21.0
4	36.5	27.5
5	45	34
7½	67	48
10	87	62
15	129	90
20	170	117
25	210	145
30	250	167
35	290	195
40	335	220
50	415	270
75	612	395
100	812	520
120	970	625
140	1 120	730
160	1 360	830
180	1 440	930
200	1 600	1 030
300	2 400	1 540
400	3 200	2 040
500	4 000	2 540

* Theoretically the current required by a *single-phase motor* is $\sqrt{3}$ or 1.732 times that required by a 3-phase motor of equal output, the supply voltage between lines, the efficiency and the power factor being the same in both cases. Actually, however, the product of P.F. multiplied by efficiency is about 1.15 times as great for a 3-phase motor as for a single-phase motor of equal output, hence the current actually required by the single-phase motor is about $1.15 \times \sqrt{3}$, or twice that required by the 3-phase machine.

Similarly, a *2-phase (3-wire or 4-wire) motor* theoretically requires $\sqrt{3}/2$ or 0.866 times the current required by a 3-phase motor of equal output, the voltage

current—but they can be obtained fitted with gearing, reducing down in a ratio as great as 100 to 1, where slow speed is required. The efficiency is low, but for such low powers the cost of running is seldom the factor that decides for or against the use of motive power as against hand power. Small motors up to, say, $\frac{1}{4}$ H.P. can be run from an ordinary lampholder, a special plug adaptor (§ 497, Vol. 2) replacing the lamp. Apart from motors for ordinary pressures of supply, they are also made for very low pressures, to work off batteries; but in this case the cost of the power is high.

Besides their application to fans and house-service pumping—the latter to a greater extent in the Dominions and America than in this country—electric motors are applicable to a number of minor domestic services. Electrically driven ‘vacuum cleaners’ have proved successful, and are most efficient in the larger sizes. Small portable cleaners are, however, usually employed in ordinary households. These machines weigh from 15 lb. upwards and consume from 200 W upwards. A vacuum of from 2 to 3 ins. of mercury is required; if it is too high, damage is done to carpets, etc. At this vacuum the smallest portable sets displace about 500 to 1 000 cu. ft. of air per hour.

Electrically driven clothes-washing machines for domestic service are a great boon. The motor is usually of $\frac{1}{4}$ to $\frac{1}{2}$ H.P. and a three-position gear box (forward, off and reverse) is provided so that a wringer can be driven from the same motor. These machines deserve to be used much more extensively than is at present the case in this country. The high first cost of the best makes is the principal obstacle to their general adoption, but, even at these prices, they constitute an excellent investment.*

The ‘electric Mary Ann’ consists of a small motor, of from $\frac{1}{8}$ to $\frac{1}{2}$ H.P., fitted with a flexible shaft and various accessories which enable it to be used for boot polishing, buffing, knife cleaning, driving a potato-peeling machine, mincing machine, coffee mill, and so on. The average housewife appears to doubt whether the advantages to be derived from such a multi-purpose motor are worth the trouble involved by carrying the machine about and

between lines, the efficiency and the power factor being the same in both cases. Actually the product of P.F. by efficiency is about 1.05 times as great for 3-phase as for 2-phase motors, hence the current required by the 2-phase motor is about 1.05×0.866 or, say, 0.9 times that required by the 3-phase motor.

* This is demonstrated in two articles (*EL. Rev.*, Vol. 97, pp. 366, 406; Vol. 99, p. 662), which deal thoroughly with the subject from the user's point of view and are also of interest to manufacturers and central station engineers.

757. Power Required for Driving Laundry Machinery.

TABLE 139.

	H.P.		H.P.
Washers, 100-200 shirts	$\frac{2}{3}$ -1 $\frac{1}{2}$	Box mangle	$\frac{1}{2}$ - $\frac{3}{4}$
Decoudin ironer	1 $\frac{1}{2}$ -2 $\frac{1}{2}$	Wringing machines	$\frac{3}{4}$ -2
Body or collar ironers	1-1 $\frac{1}{2}$	Starching machines	$\frac{1}{2}$ -1
Hydro-extractors, 2-3 ft.	2-4	Domestic washers, mangles, etc.	$\frac{1}{2}$ - $\frac{3}{4}$
„ when starting	4-6		

758. Ceiling Fans.—In this country it is rarely necessary to use ceiling fans, except in restaurants. These machines do not ventilate in the true sense of the word, but merely keep air in motion, and are therefore particularly useful in hot climates where buildings are so constructed that the problem is rather to secure the cooling influence of air in motion than to increase the natural air supply to the room (§ 763). In India, for instance, tens of thousands of slow-speed ceiling fans are now in use as a substitute for the punkah; while every first-class line of passenger steamers plying to the East is now equipped with ceiling fans in the saloons and bracket fans in the cabins. A small electric motor drives two, three, or four blades attached radially to a hub on its spindle. Motors are made suitable for direct current and for single-phase and 3-phase alternating current, but the A.C. types are seldom quite silent. The sweep of the blades is generally about 5 ft., but smaller sizes down to 2 ft. diameter are also made. For the larger sweep, the speed is generally from 150 to 200 r.p.m., while it may be anything up to 650 r.p.m. in the smaller sizes. The low-speed fans have the advantage of more silent running, while the high-speed type are more economical. The overall efficiency varies from about 25 to 40 % in various types. The majority of ceiling fans in use at present require from 110 to 160 W (0·11 to 0·16 kWh per hour), but there are innumerable types listed, down to 30 W. The standard pressures, as already stated, are 110 and 220 V, and the standard frequency for alternating supply is 50 cycles; but fans can be obtained for a margin on either side of these standards. Owing to the long hours of continuous working to which fans are subjected, the question of lubrication is of paramount importance; as the shaft is vertical it is difficult to prevent the access of oil to the armature, and

the dripping of oil from the spindle is not unknown. In one type (Swan fan) the lubricant is carried up a special groove on a fixed hollow shaft, by the revolution of the armature thereon, and the oil returns to the reservoir below through the central passage. Ball bearings when first tried were not silent enough for night work, but this defect is disappearing, and the efficiency is sensibly increased by their use. For the insulation of the armature wires impregnated silk is now used exclusively in the tropics, cotton-insulated wires having proved an expensive failure; for artificial silk see § 74—IXd, Vol. 1. The motors are series wound and the total resistance of armature and field is so high that small fans can be switched on direct, without starting resistance if so required.

Many experimental types of blade have been tried for ceiling fans, constructed of wood or aluminium, these endeavours being directed towards spreading the breeze. In point of fact, very little progress has been achieved, and the down-draught differs very little from a cylinder of the diameter of the blades. The propeller-shaped blade, with a double twist, is the most popular type, but it shows no appreciable advantage over the flat blade in the distribution of air. In some types the angle of the blades is fixed, while in others it is adjustable; an angle of from 25° to 30° with the horizontal is generally used.

Much valuable information on the subject of ceiling fans will be found in B.S.S. No. 367 (1932), "Performance of Ceiling-type Electric Fans," including a typical air-velocity curve and a standard method of computing air-delivery.

759. Speed Regulators for Fans.—The method of regulating fans by the series-parallel control of pairs has already been referred to (§§ 452, 453, Vol. 2), and diagrams showing how the connections are arranged will be found in § 506, Vol. 2. The more ordinary and convenient method, however, is to adjust the speed by means of a regulator, with several switch contacts, allowing several speeds by throwing more or less resistance into series with the motor. Usually the resistance consists of coils of fine wire, but lamps can also be utilised as resistance elements. The effect of putting a regulator into service is to absorb a certain proportion of the pressure, so that the fan motor works on reduced pressure and revolves slower. A certain amount of power is actually wasted in the resistance, but, on the other hand, the total power consumed by the combination is reduced, so that the con-

sumption recorded on the meter is less; *e.g.* if a 220 V fan at full speed takes 120 W, and 100 ohms resistance is added, the total power will be reduced to about 100 W, of which the fan uses 80 W and the regulator wastes 20 W.

760. Desk Fans.—A distinct type of fan, capable of use either as a ceiling or desk fan, is that having small blades, from 9 to 16 ins. diameter, and running generally at high speed, *viz.* from 1 000 to 2 000 r.p.m. It is necessary to have guards round the blades for these high speeds, unless the fans are out of reach, and the consequence is that humming occurs. For this reason these fans are not particularly satisfactory for night use, except in railway carriages or on ships, where the noise is hardly noticeable. This type of fan is adapted to desk or portable use; it can also be obtained hinged or pivoted, so as to be capable of being used as a bracket adjustable as to the direction in which it throws the breeze. Various means have been devised for making the fan oscillate about a mean position on a plane or elliptical (side to side, up and down) path, so as to increase its useful sphere of action. Though mainly useful as breeze-producing machines, desk or bracket fans can be arranged in a wall opening or near an open window, so as to perform a certain amount of true ventilation. See also B.S.S. No. 380 (1930), "Performance of Desk-type Electric Fans."

761. Hours of Use and Consumption of Fans.—Table 140 shows the approximate consumption of ceiling and desk-pattern fans respectively.

TABLE 140.—*Electric Fans: Power Consumption and Current.*

Type.	Watts.	Units per hour. kWh.	Current at	
			220 V.	110V.
Ceiling	100	0·1	Amps. 0·45	Amps. 0·9
	120	0·12	0·55	1·1
	150	0·15	0·67	1·3
	180	0·18	0·82	1·6
	200	0·2	0·91	1·8
Desk, etc.	30	0·08	0·14	0·28
	60	0·06	0·27	0·54
	75	0·07	0·34	0·68

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The power required by 'free' fans, simply moving air, without producing any appreciable suction or pressure, is approximately as follows :—

				H. P.
To move	1 000-	1 500	cu. ft./min. .	$\frac{1}{2}$ - $\frac{1}{4}$
" "	3 000-	6 000	" " .	$\frac{3}{4}$ - $1\frac{1}{4}$
" "	6 000-	9 000	" " .	$1\frac{1}{4}$ - $1\frac{3}{4}$
" "	20 000-	45 000	" " .	$1\frac{3}{4}$ - $3\frac{1}{4}$

Pressure and exhaust fans (§ 763) absorb more power according to the pressure difference which they produce.

In hot climates fans are often kept running day and night and sometimes for weeks on end. In England summer conditions are just temperate and erratic enough to keep many people from installing breeze fans, as distinct from pressure and exhaust fans (§ 763), where they could really be usefully employed. They are used to a considerable extent in offices, and might well be used more extensively in dwelling-houses and particularly in kitchens. Two or three desk fans could be usefully employed in most middle-class households, and should average 5 to 7 hours' use daily during hot weather. With current at 4d. a unit, the cost of running such fans would be between a 1d. and 2d. a day for each. Owing to the vagaries of our climate, the average householder is reluctant to incur the first cost of a fan; in some places they are hired out by central stations.

In an ordinary private house in the tropics, the average use of all fans may be taken as from $6\frac{1}{2}$ to 9 hours a day, during the hot weather, according to the proportion of occupied bedrooms to sitting-rooms; the total number of fans being much greater than in a corresponding house in this country. The fan season of course varies greatly with the locality.

Actual records of a number of public buildings in different parts of India give the data shown in Table 141; the fans are of ceiling type in all cases, the height varying from 8 to 10 ft. in nearly all the rooms. In exceptional cases, fans have been hung as high as 20 ft. from the floor with satisfactory results. The contrasts in Table 141 are very marked, especially in the ecclesiastical buildings; private houses are more uniform.

Analysis in the case of private houses will not serve to show the floor area usefully served, as one fan generally suffices for a room of any ordinary size. Furthermore, in public buildings, fans are for the most part used without regulators, whereas in private houses

TABLE 141.—*Fans in Public Buildings in India.*

Buildings.	kW installed.	Floor area, sq. ft. per fan.	Units (kWh) per fan per month.	Units (kWh) per kW installed per month of use.	Average daily hours of use.
Telegraph signal hall .	6.5	200	75.0	600	20
A hospital ward .	2.2	234	59.4	320	11
Four offices rooms .	2.0	217	34.0	283	8.5
A classroom .	0.44	480	13.2	120	4.0
Three public halls .	1.15	448	16.7	116	3.9
Two ballrooms .	3.5	124	24.0	21	0.6
Three churches .	3.2	420	2.4	16	0.5
A Scotch church .	1.5	164	17.0	102	3.3

regulators are always installed and the fan is often taking only half its rated input. Data from a number of private houses in Calcutta are given in Table 142:—

TABLE 142.—*Consumption of Fans in Houses in India.*

	Maximum.	Minimum.	Average.
Units (kWh) per fan per month . . .	35	9	22
Units (kWh) per kW installed per month . . .	260	77	152
Daily hours of use of all fans . . .	8½	2½	5

The term 'kW installed' or 'kW connected' means the aggregate power in kW required by the whole of the apparatus installed, when in use at one and the same time. It may, according to circumstances, refer to apparatus of all sorts or to that of one particular kind; in the above example fans and motors only are referred to, as the context shows.

762. Electric Punkah-pulling.—Many types of punkah-pulling machines, capable of being driven electrically, have been put on the market in India. The majority, however, have not been sufficiently successful to warrant extensive use. *Prima facie* a good punkah-puller system appears far more efficient than a number of separate fans, and in barracks and in public offices the former are used to a certain extent. A single motor is capable of operating a large train of punkahs, and, as great speed reduction is in any case essential, a high-speed, and therefore cheaper, motor can be used with worm-reduction gearing.

In India the installation of punkah-pullers complete cost, pre-war, from £13 to £17 per 1 000 sq. ft. served, and the power required is about 100 W for the same area; at least eight or ten fans, costing (with wiring, etc.) from £53 to £67 (pre-war), and using about 1 kW, would be needed for the same service. The following figures may also be used as a general guide:—

2	B.H.P. motor, taking 2kW, will serve 450 r.ft. of punkah.	Pre-war cost	£185
1	" " " " 1 " " " 300 " " "	" "	£160
½	" " " " 0·5 " " " 150 " " "	" "	£147

This includes starting and regulating switch, gearing, bracket, flexible coupling, shafting, cranks, pulleys, pulling rope and springs, accessories and wiring. The punkah frame and suspension must be added at about 1s. 6d. per r. foot.

For operating single swinging punkahs an ingenious system known as the 'Bandy' was introduced some years ago, but it has not made such headway as was expected.

763. Pressure and Exhaust Fans.—The fans above dealt with are little more than breeze producers or air circulators, and when it is required either to force air into, or exhaust it from, a room a totally different type is necessary. The requirements differ so much that trade catalogues must be referred to for details. Motor-driven pressure blowers are listed as small as 5 ins. diameter; these will displace from 220 cu. ft. of air per minute, at 1 750 r.p.m., against ½-in. water gauge (W.G.), when consuming about 45 W, up to 525 cu. ft. a minute at 4 000 r.p.m., against 2½-ins. W.G., with about 500 W. The largest stock catalogue size is 60 ins. diameter; this will displace from 41 000 cu. ft. of air per minute at 150 r.p.m., against 1-in. W.G., with 6 B.H.P., up to 78 000 cu. ft. a minute at 325 r.p.m., 2½ ins. W.G., with 52 B.H.P. Exhaust fans, assuming free circulation, are listed from 12 ins. diameter, taking 60 W, and displacing 1 000 cu. ft. a minute at 1 000 r.p.m., up to 42 ins. diameter, taking 550 W, and displacing 14 000 cu. ft. a minute at 350 r.p.m.

The Pitter multiblade fan is a radically distinct type. Instead of a single set of relatively wide blades, three sets of narrow blades are set one behind the other at the spacing and inclination found to give best results under the operating conditions proposed. A total blade surface greater than that of the standard type of fan is obtained, but it is claimed that eddy current losses are reduced, and that the air displacement is from 30 % (in small sizes) to 50 % (in large

sizes) greater than that of an ordinary propeller fan of equal diameter, speed and wattage.

764. Power required by Fans.—The theoretical relation between the revolutions of a fan, the volume of air it displaces, the pressure created, and the horse-power required is illustrated by Fig. 385. It will be seen that the volume varies as the speed; the pressure as the square, and the power as the cube, of the speed. Naturally these values are greatly modified in practice.

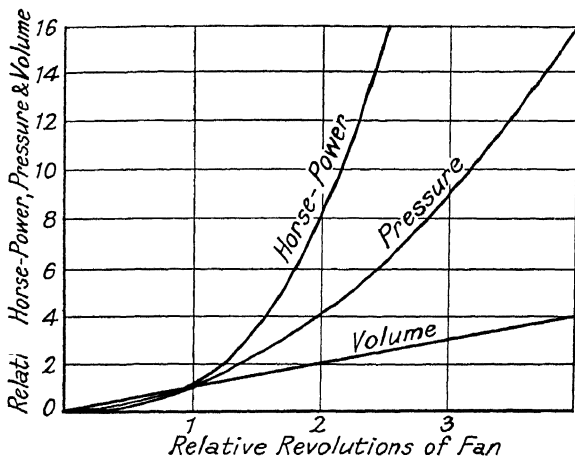


FIG. 385.—Theoretical relations between r.p.m. of fan, volume discharged, pressure created and H.P. required (*Sturtevant*).

Neglecting friction, and the pressure head necessary to overcome it, the velocity of air (or any other fluid) issuing from an orifice can be determined from the formula for falling bodies, *viz.* :—

$v = \sqrt{(2gh)}$, where v = velocity in ft. per sec.

$g = 32.1$ ft. per sec.² (at sea-level).

h = velocity head in feet (*i.e.* total head less pressure head).

But for fluids

$h = p / d$, where p is the pressure in lb. per sq. ft., and d is the density in lb. per cu. ft.

Therefore $v = \sqrt{(2gp / d)}$ as applied to the velocity of movement of fluids. In practice, friction would restrict the freedom of flow and part of the head or pressure would be expended in overcoming

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the resistance; this is known as the pressure head and the balance as the velocity head. If there is a free outlet, *i.e.* if the fluid does not have to traverse any pipe or passage, but only an orifice, the pressure head disappears and the velocity will be practically that calculated by the formula. In the case of the atmosphere the density varies at different heights, but by assuming it constant an ideal or equivalent head can be determined which will *weigh the same and exert the same pressure* per unit area. Under normal barometer, *viz.* 29.9 ins., atmospheric pressure is 2 110 lb. to the square foot, and at 50° F. a cubic foot of air weighs 0.078 lb.; so a homogeneous column $2\,110 / 0.078 = 27\,000$ feet high and 1 square foot area of base would fulfil the above conditions. If air under this head were allowed to flow into a vacuum, the velocity would be $v = \sqrt{(2gp / d)} = \sqrt{(64.2 \times 2\,110 / 0.078)} = 1\,315$ ft. per sec. Other values of the density of air are:—

At 0° F.	density 0.086 lb./cu. ft.	At 150° F.	density 0.065 lb./cu. ft.
„ 32° F.	„ 0.081 „ „	„ 212° F.	„ 0.059 „ „
„ 100° F.	„ 0.071 „ „	„ 350° F.	„ 0.049 „ „

The relative volume of a given weight varies as the absolute temperature, *i.e.* as $(461 + t)$, where t = temperature in degrees Fahrenheit. In the case of air under pressure in a reservoir there is no actual column of air, but the height, h , of the equivalent homogeneous column = p / d as before, and this height may be used in calculations.

If pressure is expressed in inches of water gauge, H , then the height, h ft., of the equivalent column of air is given by $h = (\text{density of water in lb. per cu. ft.} \times H) / (12 \times \text{density of air in lb. per cu. ft.})$ feet, and, at a temperature of 50° F., $h = (62.4 \times H) / (12 \times 0.078) = 66.8 H$ ft. Substituting this value in the formula for velocity, $v(\text{at } 50^\circ \text{ F.}) = \sqrt{(64.2 \times 66.8 H)} = 65.5 \sqrt{H}$ ft. per sec., from which may be determined the approximate velocity of efflux of air under any given pressure expressed in inches of water gauge.

In the case of air, which is compressible when pressure is applied and expansible by heat, the density varies with the pressure, and a change of temperature also affects the results. The effect of increased density, which may be produced by the pressure, is to decrease the ideal velocity head; for if $h = p / d$ it is evident that an increase in d must, for a given pressure, reduce

the value of h . A similar influence is exerted by temperature, for by an increase in temperature the density is decreased, and hence the value of h is increased. The velocity being dependent on the ideal head, it is necessary that comparisons be reduced to the same conditions of pressure, temperature, and density.

Expressing the pressure, p , in *ounces per square inch*, and d as the weight (0.078 lb.) of a cubic foot of dry air at 50° F. under normal atmospheric pressure of 14.7 lb. or 235 oz. per sq. in., the formula becomes:—

$$v = \sqrt{64.2 \times p \times 144 / [16 \times 0.078 \times (235 + p) / 235]} \\ = \sqrt{1\,747\,000 \times p / (235 + p)} \text{ ft. per sec.}$$

If the pressure is expressed as H , *inches of water gauge*, then $v = \sqrt{1\,747\,000 \times H / (407 + H)}$ ft. per sec. These formulæ take into account the compression of the air due to its pressure, but make no allowance for change of temperature during discharge. As stated above, any decrease in the density of the air due to higher temperature must, for the same pressure, increase the value of h , and therefore of the velocity also. If the velocity and consequently the head are to be maintained constant, under varying temperatures, the pressure must decrease proportionately to the density as affected by the absolute temperature.

For example, under a pressure of $2\frac{3}{4}$ oz. per sq. in. or $4\frac{1}{2}$ ins. of W.G. the velocity at 50° F. is 142 ft. per sec. or 8 520 ft. per min. by the above formulæ. Suppose the orifice to have an effective area of 6 sq. ins. and the total pressure will be $16\frac{1}{2}$ oz. or 1.03 lb. Then the theoretical power required will be $8\,520 \times 1.03 / 33\,000 = 0.266$ H.P. and the volume discharged 854 cu. ft. per min. The effective area at the *vena contracta* may vary from about 0.6 to nearly the full actual area.

If the temperature is 150° instead of 50° F., *i.e.* 611° instead of 511° absolute, the volume of a given weight is increased in proportion and the relative density will be $511 / 611 = 0.84$. The actual density will be $0.078 \times 0.84 = 0.065$ lb. per cu. ft. In this case the pressure necessary to produce the same velocity and volume as before will be $2\frac{3}{4} \times 0.84 = 2.3$ oz. per sq. in., or, on the whole area of 6 sq. ins., 13.8 oz. = 0.86 lb. total; the theoretical power required will similarly be $0.266 \times 0.84 = 0.224$ H.P.

On the other hand, the relative *volume* of the same *weight* of air, expanded by the increase in temperature from 50° to 150°, will be the reciprocal of the above figure, $611 / 511$ or 1.2, and this will also be the relative velocity necessary to move the same weight of air in a given time. The actual velocity will therefore be $142 \times 1.2 = 170$ ft. per sec. or 10 200 ft. per min. The relative pressure required to produce this velocity will also be 1.2, *i.e.* 3.3 oz. per sq. in. or 5.6 ins. W.G. The theoretical power will be increased to $10\,200 \times 3.3 \times 6 / 33\,000 \times 16 = 0.382$ H.P.

The relations illustrated by the preceding examples are of great practical importance. Thus, where a definite volume of air (cu. ft.

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per min.) has to be delivered at a certain velocity, *e.g.* for purposes of ventilation, the horse-power required decreases as the temperature of the air rises. On the other hand, where a definite weight of air (lb. per min.) has to be delivered, the velocity must be increased as the temperature rises (to allow for the lower density of the air); the H.P. absorbed therefore increases. If possible, the fan should be installed where it deals with cool air.

Suppose, for example, that a fan forcing air at 90° F. (551° absolute) through a preheater absorbs 10 H.P. If the fan were placed at the preheater outlet where the air is at, say, 400° F. (861° absolute), the power consumption would be $861 / 551 = 1.55$ times as great, *i.e.* about 15 H.P.

While the volume of air delivered by a fan varies directly as the speed, the power required to drive it increases as the *cube* of its speed; for the power is here the product of the pressure and the velocity, and the former increases as the square of the speed. The work done by a fan in foot-lb. per second = $dav^3 / 2g$,

where d is the density in lb. per cu. ft.

a the effective area in sq. ft.

v is the air velocity in ft. per sec.

Taking g as 32.1 ft. per sec.², the applied H.P. = $(dav^3 / 35\ 300) \times (100 / E)$, where E is the efficiency; this may vary from about 30 per cent. to 40 per cent. with straight-bladed fans, to 50 per cent. with curved forward bladed fans, or even higher in large sizes. In the case of an electrically driven fan the losses in the motor must also be taken into account in determining the power consumption in kWh; for motor efficiencies *see* Tables 113, 114, § 672, and paragraphs on individual types of motors in Chapter 28.

Another approximate formula, correct at about 50° F., is B.H.P. = $(V \times W.G. \times 5.2 / 33\ 000) \times (100 / E)$, where V is the volume of air in cu. ft. per min.; this, however, takes no account of alterations in density.

By way of practical example, suppose we require to deliver 80 000 cu. ft. of air per min. at a temperature of 50° F., under a pressure of $2\frac{1}{2}$ ins. W.G. or 1.47 oz. per sq. in. By the formula the theoretical velocity is indicated as 105 ft. per sec., corresponding to a discharge of 43 cu. ft. per min. per sq. in. of effective area. Therefore to obtain the required discharge the effective area should be $80\ 000 / 43 = 1\ 860$ sq. ins. or 12.9 sq. ft. Then the *theoretical* power required may be found either by

$$\text{H.P.} = (\text{velocity} \times \text{total pressure}) / 550$$

$$= 105 \times (1\ 860 \times 1.47) / 550 \times 16;$$

$$\text{or by H.P.} = (dav^3) / 35\ 300 = (0.078 \times 12.9 \times 105^3) / 35\ 300;$$

$$\text{or again by H.P.} = (V \times W.G. \times 5.2) / 33\ 000$$

$$= (80\ 000 \times 2.5 \times 5.2) / 33\ 000.$$

TABLE 143.—*Outputs and Power Requirements of Sirocco Single-Inlet, Cased Full-Width Fans.*

(By courtesy of Messrs. Davidson & Co. Ltd.)

NOTE.—There are standard sizes intermediate between those tabulated below (e.g. 7½, 12½, 17½, 25 ins., etc.); their speeds, outputs and H.P. can be interpolated for purposes of general estimates.

Fan Diameter, Inches.		Static Water Gauge, in Inches.*					
		½	1	1½	2	2½	3
5	R.P.M.	1 770	2 540	3 115	3 615	4 000	4 384
	Cu. ft. per min.	230	340	415	480	525	580
	B.H.P.	0·032	0·095	0·17	0·27	0·37	0·5
10	R.P.M.	885	1 270	1 560	1 800	2 000	2 190
	Cu. ft. per min.	970	1 420	1 740	2 020	2 200	2 418
	B.H.P.	0·14	0·4	0·75	1·1	1·6	2·0
15	R.P.M.	585	840	1 030	1 200	1 330	1 450
	Cu. ft. per min.	2 245	3 275	4 020	4 670	5 080	5 585
	B.H.P.	0·31	0·9	1·75	2·6	3·5	4·75
20	R.P.M.	460	630	775	900	995	1 090
	Cu. ft. per min.	3 930	5 737	7 037	8 180	8 890	9 780
	B.H.P.	0·55	1·6	3·0	4·5	6·25	8·25
30	R.P.M.	290	420	520	600	660	726
	Cu. ft. per min.	9 290	13 540	16 610	19 300	20 980	23 090
	B.H.P.	1·25	3·75	6·75	11·0	14·5	19·0
40	R.P.M.	230	315	385	450	495	545
	Cu. ft. per min.	16 315	23 800	29 210	33 950	36 890	40 595
	B.H.P.	2·25	6·5	12·0	19·0	26·0	34·0
50	R.P.M.	175	255	310	360	400	440
	Cu. ft. per min.	25 840	37 710	46 275	55 790	58 440	64 305
	B.H.P.	3·5	10·5	19·0	31·0	41·0	54·0
60	R.P.M.	146	210	258	300	330	363
	Cu. ft. per min.	37 670	54 890	67 460	78 410	85 210	93 750
	B.H.P.	5·25	15·0	28·0	44·0	60·0	79·0

* AUTHORS' NOTE.—It is particularly to be noted that the pressures given in this table are static water gauge values, i.e. the pressures actually available at the fan outlet to overcome the resistance in the air circuit to which the fan is applied. Some manufacturers quote 'total water gauge' pressures, i.e. the static water gauge pressure plus the pressure absorbed in overcoming the internal resistance of the fan and in imparting velocity to the air. Though the total water gauge is of interest as regards the overall efficiency of the fan, the static water gauge is what concerns the user, as this alone is the pressure available to drive air through his ducts, etc. The distinction between the two methods of rating is vital but is not always made clear, particularly when total water gauge figures are cited. Whereas the fan efficiency calculated with reference to the static water gauge cannot be higher than about 52 %, efficiencies of 70-80 % can be obtained when calculations are based on the total water gauge. Where total water gauge figures are given, it should be ascertained how much of the total pressure is absorbed internally by the fan. The correct application of fans is as important as the choice of a good fan of suitable size. In particular, a suitable expanding outlet on the fan greatly improves the performance by converting velocity to pressure.

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The answer in each case is about 33 H.P., so that with a fan efficiency of 40 % the motor must deliver 82 B.H.P. The fan in practice would be somewhat larger than is indicated by the area found above, say 55 ins. or 60 ins. diameter, according to type and design.

Table 143 shows the output and power requirements of single-inlet, 'full width' Sirocco centrifugal fans, these being suitable for handling large volumes of air at moderate pressures. The outputs and power requirements of double-inlet fans are twice those shown in the table for single-inlet fans of the same diameter.

'Three-quarter width' fans (*i.e.* fans of three-quarters the width of the 'full-width' fans of equal diameter) are supplied for higher pressures up to 5-in. static water gauge (*see* footnote to Table 143). Up to 3-in. static water gauge these fans are driven at the same speeds as the 'full-width' fans of equal diameter and have then approximately 70 to 75 % of the output and power requirements of the full-width fans. For 5-in. static water gauge, they are driven at about 1.28 times the speed required for 3-in. static water gauge; they then deliver 1.28 times the volume of air, corresponding to 3-in. static water gauge, and absorb about 2.1 times the horse-power. Table 143 does not apply to the special type of fan made for dust-removal purposes.

Care should be taken that the fans in any installation are operated under the conditions for which they are designed. The output from a given fan can be increased by increasing the revolutions per minute, but this involves a disproportionate increase in H.P. absorbed, owing to loss of efficiency. Except for temporary service or in emergency, a fan should never be driven above its rated speed; a larger fan should be installed where greater delivery is desired.

765. Passage of Air through Ducts.—Where air has to be forced through pipes or ducts the pressure head, or loss due to friction, is proportional to the surface with which the air comes in contact, *i.e.* it varies directly as the length and inversely as the diameter of a pipe; it also varies with the square of the velocity. Sturtevant (*Mechanical Draft*) gives the following formulæ for smooth galvanised iron pipes with all laps extending in the direction of the air movement:—

$$\begin{aligned} p &= lv^2 / 25\,000d \\ l &= 25\,000dp / v^2 \end{aligned} \qquad \begin{aligned} v &= \sqrt{(25\,000dp / l)}, \\ d &= lv^2 / 25\,000p, \end{aligned}$$

where p = loss of pressure in oz. per sq. in.
 v = velocity in feet per second.
 l = length of pipe in feet.
 d = diameter of pipe in inches.

Thus in 100 ft. of 60-in. pipe, with a velocity of 100 ft. per sec., the loss of pressure would be 0.667 oz. per sq. in. or 1.16 in. W.G., and at half the velocity the loss would be one-quarter of this, or 0.167 oz. The theoretical amount of power required to move a given volume of air is measured by the product of the distance moved and the total resistance overcome. Thus, if air is moved under a pressure of 8 oz. per sq. in., tables show that the issuing velocity will be about 14 380 ft. per min.; if the effective area of discharge is 6 ins. the total pressure will be 48 oz., or 3 lb. Then the work done is $14\,380 \times 3 = 43\,140$ ft.-lb. per min., or $1\frac{1}{8}$ H.P. This takes no account of the inefficiency of the blower or of frictional losses.

For ascertaining the resistance when air is passed through ducts the following formula (agreeing with Sturtevant's) is given by Unwin:—

$$R \text{ (at } 50^\circ \text{ F.)} = LV^2 / 14\,450d,$$

where R = resistance in inches water gauge.
 L = length of duct in feet.
 V = velocity of air in feet per second.
 d = diameter of circular duct or length of side of square duct in inches.

Thus in a particular case L was 135 ft.; V was 370 ft. per min., or 6.1 ft. per sec.; $V^2 = 37.5$; and d was 14 ins. Then $R = 0.025$ in. W.G., or 0.014 oz. per sq. in. There is a small correction according to the absolute temperature of the air. From the above formula, where R is known,

$$\text{Cubic feet of air per minute} = 40\sqrt{d^5 R / L} \text{ for circular ducts.}$$

$$\text{,, ,, ,, ,,} = 50\sqrt{d^5 R / L} \text{ for square ducts.}$$

$$\text{Diameter of round duct} = \sqrt[5]{(c / 40)^2 \times L / R}.$$

$$\text{Side of square duct} = \sqrt[5]{(c / 50)^2 \times L / R},$$

where c = cubic feet of air per minute.

766. Air Compressors.—The quadruplex single-stage compressor is probably the most generally useful type of air compressor for small or medium outputs, up to about 500 cu. ft. of

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free air compressed to pressures from 20 to 120 lb. per sq. in. This machine has four radial cylinders with trunk pistons, and the four connecting rods all operate on the same crank pin. When roller bearings are used on the crankshaft and crankpin, the compressor can be driven at high speed and is suitable for direct coupling to an electric motor. Such a compressor with a direct-coupled motor is relatively light and compact; when mounted on a truck it can be taken near to the compressed-air tools in workshop, field, mine, etc., thus eliminating the cost of permanent distribution pipes, and the frictional and leakage losses arising therefrom.

TABLE 144.—*Horse-Power Required by Quadruplex Air Compressors.*

(By courtesy of Messrs. Reavell & Co. Ltd.)

Size.	R.P.M.	Piston Displacement. Cu. Ft./Min.	Brake Horse-power † Required for Delivery Pressure, lb. per Sq. In.			
			20 lb.	60 lb.	100 lb.	120 lb.
QR 6 × 4	400	102		13	17	18
	600	152	13	22	26	27
	800	203	22	33	38	40
QR 7½ × 5	400	199	16	26	34	
	600	298	25	44	52	58
	700	348	34	53	63	66
QR 9 × 6	400	347	27	44	58	
	600	520	43	75	93	60

* The free-air volume compressed and delivered at 100 lb. per sq. in. is about 80 % of the piston displacement.

† At the compressor shaft. For continuous operation it is advisable to add 5 % to these figures; and where gearing or a belt is interposed between the motor and the compressor, at least a further 5 % should be added to cover the power loss in the transmission.

Table 144 shows the horse-power required at the compressor shaft by quadruplex compressors of various capacities. These figures correspond roughly to 700, 440, 350, and 330 cu. ft. of free air per kWh delivered at 20, 60, 100, and 120 lb. per sq. in. respectively. For comparison, the data in Table 145 are reproduced * showing the air output and cooling water requirements of

* From *Power Engineer*, Vol. 23, p. 286.

reciprocating and sliding-vane rotary compressors rated at from 105 to 125 cu. ft. of free air per min.

TABLE 145.—*Comparison Between Small Reciprocating and Rotary Compressors.*

Compression.	Type of Compressor.	Cu. Ft. of Free Air Compressed per kWh.	Cooling Water, Gallons per 100 Cu. Ft. of Free Air Compressed.
Single-stage to 44 lb. gauge	Rotary	520	1.6
	Reciprocating	510	1.1
Two-stage to 88 lb. gauge	Rotary	354	2.9
	Reciprocating	425	1.6

Where larger quantities of compressed air are required, at pressures up to 120 lb. per sq. in., vertical double-acting, two-stage compressors may be employed. The low-pressure and high-pressure cylinders are side by side, and the connecting rods and crankshaft run inside a closed crankcase. Typical data for these machines are given in Table 146.

A reciprocating compressor, provided with by-pass valves to enable the machine to start light, needs about 30 % of full-load torque to overcome static friction and about 25 % of full-load torque to bring it up to full speed.

TABLE 146.—*Horse-Power Required by Vertical, Double-Acting, Two-Stage Air Compressors.*

(By courtesy of Messrs. Reavell & Co. Ltd.)

Size.	Cu. Ft. Free Air per Min.	R.P.M.	B.H.P. at 120 lb. per Sq. In.*	Size.	Cu. Ft. Free Air per Min.	R.P.M.	B.H.P. at 120 lb. per Sq. In.*
VC 6	500	480	110	VC 12	2 000	262	450
VC 8	750	415	165	VC 14	3 000	240	675
VC 9	1 000	360	225	VC 16	4 000	240	900
VC 10	1 500	320	340	VC 17	5 000	222	1 125

*For 100 lb. per sq. in. delivery pressure, the B.H.P. required is about 93 % of the values stated above.

Centrifugal or turbo-compressors are used where very large quantities of compressed air are required, as for mining service. Standard sizes of such machines compress from 3 000 to 18 000

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cu. ft. of free air per min., delivering it at pressures up to 120 lb. per sq. in. (gauge). A typical installation of this class consists of a compressor delivering 8 800 cu. ft. of free air per min. at 90 lb. (gauge), driven at 5 600 r.p.m. by a 2 000 H.P., 1 485 r.p.m., 5 000 V, 50-cycle induction motor through double-helical gearing.

Rotary blowers and exhausters are convenient for dealing with air, or other gases, at moderate positive pressures or partial vacua. In the 'crescent type' blower a drum, rotating eccentrically inside a cylindrical casing, is provided with sliding radial vanes which are driven outwards by centrifugal force when the drum rotates. The crescent-shaped space between the drum and the casing is divided, by the vanes, into a number of pockets which decrease in volume as they approach the delivery side. Air drawn in at atmospheric pressure is thus delivered at a positive pressure; or air extracted from a partial vacuum is compressed and expelled at slightly above atmospheric pressure. If the vanes actually rub against the casing there is considerable loss of power by friction and the permissible speed of rotation is low. In an improved form of the machine, known as the 'rolling-drum' type, the vanes bear on a cylindrical liner carried by roller bearings and running inside the casing with very small clearance. This liner has diagonal lines of perforations to allow the air to enter and leave the pockets formed by the vanes, and it is carried round with the latter by their radial pressure on its inner surface. Friction being thus practically eliminated, the 'rolling-drum' compressor or exhauster can be driven at high speed by a direct-coupled motor; typical data are given in Table 147. The applications of this type of machine include the supply of low-pressure air for agitation, pneumatic transport, atomising, scavenging, sand blasting, etc.; and low-pressure gas for distribution or furnaces; also, as an exhauster, for priming centrifugal pumps, operating vacuum pumps, and so on.

Points to be watched in any compressed air installations are as follows:—

(1) Efficient filters should be used on the suction inlet to prevent the wear and frictional loss which would be caused by dust being drawn into the machine. The filters should be kept clean, otherwise waste of power and reduction of capacity will result.

(2) An automatic 'unloading' valve should open the discharge side of the compressor to atmosphere when the desired pressure has been reached in the air receiver. The alternative is to continue to force air into the receiver, meanwhile blowing off an equal volume through a safety valve on the receiver; this is obviously

wasteful of power. The unloading valve must be opened by a relay or servo-motor when the desired pressure is reached in the receiver; it must not require any appreciable pressure to hold it open, otherwise the compressor has still to compress air, which is then blown to waste. Alternatively, the 'unloading' valve may close the suction inlet so that the compressor pistons run *in vacuo* as long as the receiver is fully charged. Where the compressor is driven by a D.C. motor the speed of the latter may be varied automatically to suit the demand for compressed air.

TABLE 147.—*Horse-Power Required by Rolling-Drum Type Rotary Air Compressors and Exhausters.*

(By courtesy of Messrs. Reavell & Co. Ltd.)

Size.*	R.P.M.	Compressing.								Exhausting.			
		Cu. Ft. Free Air Delivered per Min. at				B.P.H.† Required at				Cu. Ft. Aspired Air Dealt with per Min. at Ins. Mercury Vacuum.		B.H.P.† Required at Ins. Mercury.	
		5 lb.	10 lb.	15 lb.	20 lb.	5 lb.	10 lb.	15 lb.	20 lb.	10".	20".	10".	20".
R 3½ × 5	2 000	29	24	—	—	1½	2	—	—	25	13	1½	2
	2 500	40	35	—	—	2	2½	—	—	39	25	2	2½
	3 000	51	46	—	—	2¾	3½	—	—	48	36	2½	3½
R 5 × 5	1 750	60	52	45	—	3½	4	5½	—	52	42	2½	3½
	2 200	78	70	62	—	4½	5½	7	—	70	57	3½	4½
	2 600	94	85	78	—	6¼	7½	9	—	85	70	4	5½
R 6 × 8	1 500	132	112	92	—	6½	9	12	—	110	92	5½	6½
	1 880	174	154	134	—	9¼	12¼	15½	—	145	129	7½	8½
	2 250	215	194	175	—	12¼	16	19½	—	180	165	9	10
R 8 × 12	1 150	270	242	210	180	11	15½	21	26	—	—	—	—
	1 440	344	316	284	252	15½	21½	27¾	33¾	—	—	—	—
	1 725	419	390	358	320	21¼	28	35½	43½	—	—	—	—
R 12 × 18	750	680	620	530	430	25	33	44	54	—	—	—	—
	940	830	730	690	580	33	43	57	70	—	—	—	—
	1 125	990	930	840	740	43	55	71	89	—	—	—	—
R 18 × 27	500	1 420	1 260	1 100	960	46	77	108	138	—	—	—	—
	625	1 800	1 625	1 470	1 330	61	96	132	168	—	—	—	—
	750	2 170	2 000	1 840	1 700	77	117	160	210	—	—	—	—

*Intermediate sizes are available, but the above Table indicates the range and requirements of these machines.

†At the compressor or exhauster shaft. For continuous operation add 5 % to these figures and, where a gear or belt drive is employed, add a further 5 % to allow for the power loss therein.

(3) Some makes of air compressors are far from being perfectly balanced; the effect of any out-of-balance forces must be considered.

(4) Permanent pipe lines and air hoses should be of sufficient diameter to prevent excessive pressure drop due to frictional resistance.

(5) The whole of the compressed air system should be tested frequently for leaks; these are often very serious in an extensive network.

767. Electric Driving of Water Pumps.—The principal types of water pumps are mentioned in the succeeding paragraphs, with special reference to their characteristics as influencing the choice of driving motor. In general, centrifugal and turbine pumps may be direct coupled to high-speed electric motors, whereas ram pumps run at such low r.p.m. that they are usually driven through single or double reduction helical gearing. Usually pumping is a long-hour service and the driving motor must be rated for continuous operation. It is, however, an easy matter to start and stop electrically driven pumps automatically by means of float switches, pressure-controlled switches, or other devices. Either horizontal or vertical shaft motors may be used, a vertical shaft motor direct coupled to a multi-stage centrifugal pump being very useful in pumping out boreholes, etc.

Pump-driving motors are often, by reason of their situation, liable to be flooded, and in some cases it is convenient to immerse the motor and pump in order to retain the advantage of direct coupling, whilst avoiding suction pipe, foot valve and the necessity of priming. Several types of motors have been developed for continuous operation under water. In one of these,* the motor rotor is used as the water impeller, thus eliminating the glands otherwise required. The machine is a squirrel-cage motor with the stator core and winding enclosed by a water-tight, non-corrodible casing filled with transformer oil. Water entering at one end of the machine flows through ducts in the rotor to the impeller bolted on to the other end of the rotor. Whether the machine is used above or under water, the windings are cooled very effectively by the oil and water.

768. Water Data and Calculation of Power in Pumping.—Since work done at the rate of 33 000 ft.-lb. a minute (550 ft.-lb. a sec.) is equal to 1 horse-power, it is necessary to know the weight of water to be pumped in a given time and the total height to which it is to be raised.

* The 'Electromersible' pump; see *El. Rev.*, Vol. 102, p. 572.

1 cu. ft. of water	= 6.235 gallons (<i>Imp.</i>) = 7.48 U.S.A. liquid gallons = 62.35 lb. = 0.02832 cu. metre = 28.32 litres.
1 gallon (<i>Imp.</i>) of water	= 0.16 cu. ft. = 10 lb. = 1.2 U.S.A. liquid gallon = 0.004546 cu. metre = 4.546 litres = 4.536 kg.
1 U.S.A. liquid gallon	= 0.833 gallon (<i>Imp.</i>).
1 cusec (cu. ft. per sec.)	= 6.24 gallons (<i>Imp.</i>) or 62.4 lb. per sec. = 374 " " 3740 " " min. = 22 440 " " 224 400 " " hr. = 0.0283 cu. meter per sec.
1 cu. metre (m. ³)	= 35.31 cu. ft. = 2 200 lb. = 220 gallons (<i>Imp.</i>) = 264 U.S.A. liquid gallons.
1 m. ³ per sec.	= 35.31 cusecs.
1 ft. head of water	= 0.435 lb. per sq. in.
1 lb. per sq. in.	= 2.3 ft. head of water.

The total height to which water has to be raised must include an allowance for the friction losses in the pipes and bends, over and above the vertical lift. Many formulæ and tables are given by as many authorities for ascertaining the loss of head in friction in straight pipes; see § 247, Vol. 1.

As regards the friction in small pipes, Table 148 gives the loss of head, L , in ft. per 100 ft. of pipe, and the quantity, Q , in gallons per minute at various velocities, in feet per second.

As pipes seldom remain clean, it is as well to be on the safe side, and the above values allow a margin for this. The loss of head in bends is usually small compared with the above, and, so far as domestic pumping is concerned, an addition of 5% to the above friction losses will generally more than cover it. For friction losses in larger pipes, Chapter 10 on Water Power may be consulted (§ 247, Vol. 1).

The only useful part of the work done in pumping is that expended in overcoming the static head. The additional head corresponding to the frictional resistance of the pipe line involves a waste of energy analogous to the I^2R loss in an electrical conductor. Pumping is generally a long-hour service, hence it pays to install large pipes in order to keep the frictional loss down to a minimum. In particular, it is usually advisable to fit an

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enlarging adapter (a length of tapered pipe) to a centrifugal pump so that the diameter of the pipe line can be larger than that of the pump outlet.

In speaking of the vertical lift, it must be understood that this includes both the suction and delivery. As regards the former, the theoretical limit of suction at sea-level is about 33 ft. or the height at which a water barometer tube would normally stand. In practice it is not possible to get nearly a perfect vacuum in a hydraulic pump, and the limit of suction actually obtainable is

TABLE 148.—*Discharge and Loss of Head in Small Water Pipes.*

Diam. Inches.		Velocity, in Feet per Second.									
		1	2	2·5	3	3·5	4	4·5	5	5·5	6
1	Q	2·02	4·05	5·0	6·06	7·18	8·1	—	—	—	—
	L	0·8	2·8	4·3	5·8	7·8	9·5	—	—	—	—
2	Q	8·1	16·2	20	24·3	28·7	32·4	36·8	40·5	—	—
	L	0·4	1·6	2·5	3·5	4·7	6·2	8	10	—	—
3	Q	18·4	36·8	45·5	55	64·3	73·6	82·3	91·6	100	110
	L	0·3	1·1	1·7	2·1	2·9	3·7	4·7	5·8	7	8·3
4	Q	32·7	65·5	81	98	114	131	146	162	179	195
	L	0·2	0·65	1·0	1·4	1·9	2·5	3·2	4·0	4·8	5·6
5	Q	51	102	127	153	179	204	228	256	279	306
	L	0·15	0·45	0·73	1·0	1·4	1·9	2·4	2·9	3·5	4·2
6	Q	73·5	147	182	220	256	293	331	368	403	440
	L	0·1	0·36	0·56	0·8	1·1	1·5	1·8	2·3	2·8	3·2

about 24 ft. with plunger-type pumps, varying with the size. Centrifugal and turbine pumps create but little suction and therefore generally require priming at the start, after which they can maintain the suction; auxiliary pumps can be arranged to prime the main pumps automatically. Centrifugal or turbine pumps may with advantage be submerged, and in any case it is advisable to reduce the suction head as far as possible by dropping the pump, *i.e.* placing as much as possible of the pipe line on the delivery side of the pump. To eliminate all possibility of an air trap, the suction pipe should rise continuously.

The horse-power required to deliver *Q* Imperial gallons per min.

against a total head of H ft. is $\text{H.P.} = QH / 33 E = 0.03 QH / E$, where E = overall efficiency (*per cent.*) of pump, motor and gearing, if any. Since the equivalent pressure $P = 0.435 H$ lb. per sq. in., the above formula may also be written:

$$\text{H.P.} = QP / 14.4 E = 0.07 QP / E.$$

These formulæ are very convenient if a suitable value is known for the overall efficiency $E\%$. Generally, it is preferable to proceed by stages, as explained below.

Having ascertained the total head, and the weight of water to be lifted per minute, the product of these quantities, divided by 33 000, gives the pump horse-power (P.H.P.). The brake horse-power (B.H.P.) required to drive the pump must next be found, by dividing the B.H.P. by the percentage efficiency of the pump. The efficiency is a very variable factor, but in all small sizes of centrifugal pumps, such as are commonly used for domestic electric pumping, it is very low—from 30 to 40 %. In large sizes of turbine* or ram pumps the efficiency may rise as high as 80 or even 85 %. For pump efficiencies of 40, 60 and 85 % with a small allowance for pipe losses, the following round figure rule will give the B.H.P. required for driving the pump *viz.* :

$$\text{B.H.P.} = \text{Gall. per min.} \times \text{Lift in ft.} / 1\ 400 \text{ or } 2\ 100 \text{ or } 2\ 900.$$

Motors are listed by manufacturers according to their rated output in B.H.P., but two ratings are often given according to whether the work is to be intermittent or continuous; for pumping the continuous rating must be taken. The efficiency of very small motors up to 1 B.H.P. may be taken as varying from 65 to 70 % and up to 3 or 4 B.H.P. as 70 to 80 %. This must be taken into account when ascertaining the electrical horse-power (E.H.P.) at the motor terminals and the probable consumption of energy and the current in the wires; and if belt or gear driving is used the loss in the drive (5 % upwards) must also be taken into account.

In order to ascertain roughly the kilowatts required to drive a motor pump, the following approximate rule may be used, on the lines of that given above for mechanical power:

$$\text{kW to motor} = \text{Gallons per minute} \times \text{Lift in ft.} / K,$$

where K has the following values:—

* Useful curves of efficiency, horse-power, and revolutions per sec. of centrifugal and turbine pumps will be found in a paper by J. T. Rossiter in the *Engineer* for June 12th and 19th, 1914.

	Pump Efficiency.	Motor Efficiency.	Value of K .
Small pumps .	0.4	0.7	1 300
Medium pumps	0.6	0.8	2 200
Large pumps .	0.85	0.9	3 400

EXAMPLE.—Assume that 3 000 gallons an hour are to be pumped up a vertical lift of 60 ft. in a 3-in. pipe 350 ft. long. Then weight of water per min. is 500 lb. The velocity in the pipe will be about $2\frac{1}{2}$ ft. per second, and the loss of head about 2 ft. per 100 ft. length (Table 147), or 4.9 ft. in all. Hence the total head will be practically 67 ft. The work to be done by the pump will be $500 \times 67 / 33\ 000$ or practically 1 pump H.P.

Assume that a centrifugal pump with an efficiency of 80 % only is to be used, and the power required to drive it will be $1 / 0.8$ or 3 B.H.P. If gearing or a belt is used, there are the extra losses of these to be taken into account, and in practice at least a $3\frac{1}{2}$ B.H.P. motor (continuous rating) would be used. If the efficiency of the motor is 80 %, the input will be 4.4 E.H.P. or (multiplying by 0.746) 3.3 kW. This is equal to 15 A at 220 V or 30 A at 110 V. The consumption of energy will in either case be 3.3 units per hour. If the price per unit is 2d., this works out to 2½d. per 1 000 gallons.

Using the rough formula for the power consumption of small pumps given above we have

$$500 \text{ gals. per min.} \times 67 \text{ ft.} / 1\ 300 = 2.6 \text{ kW,}$$

the difference being due to the very low pump efficiency now assumed and the extra allowance given to the motor.

The cost of pumping by larger machines is, of course, much lower. For example, the double suction turbine pumps installed at Minneapolis some years ago delivered 24 million gallons daily through a 50-in. pipe 19 000 ft. long, against a head of 235 ft., of which friction accounted for 18 ft. The pump efficiency was over 80 %. A 1 200 H.P., 2 200 V, 3-phase induction motor drove the pump at 514 r.p.m. The overall efficiency of the set was 75 %, and the cost was stated to be 0.22d. per 1 000 gallons at 0.19d. per kWh. The rating of the motor in this case (which was taken from an account in a technical paper) must have been very conservative, as the theoretical water horse-power is 1 180. The rough formula stated above for the B.H.P. of large pumps gives a more generally acceptable result, *viz.* :

$$\frac{24\ 000\ 000}{24 \times 60} \quad \frac{235}{2\ 900} \quad 1\ 500 \text{ B.H.P.}$$

As an example of high-head pumping in Simla, 20½-million gallons a year are pumped up against a head, including friction, of

2 800 ft. with a consumption of 340 500 kWh. This corresponds to an overall efficiency of

$$\frac{20\,500\,000 \times 10 \times 2\,800}{340\,500 \times 2\,656\,400} \times 100, \text{ or } 63\% \text{ (approx.)}$$

(1 kWh = 2 656 400 ft.-lb.).

769. Ram Pumps.—Each working stroke of a reciprocating ram pump delivers a definite volume of water, regardless of the head, hence the horse-power absorbed increases directly with the speed of the pump and directly with the head to be overcome.

For example, if a ram pump absorbs 10 H.P. at 50 r.p.m. and 30 ft. head, it will consume, at 55 r.p.m. and 35 ft. head, $10 \times (55/50) \times (35/30)$, or 12.8 H.P. approximately.

The delivery, Q , in gallons per minute may be found by the formula

$$Q = a \times n \times v \times 6.25 \times c,$$

where a = area of one ram in sq. ft.

n = number of rams.

v = effective speed of rams in ft. per min., *i.e.* half the actual ram speed, as only the forward stroke is effective.

c = percentage slip, say 0.85 to 0.9 to allow for sluggishness in the valves.

By transposition the area, and therefore the diameter, of the rams for a given delivery can be found, and the stroke and revolutions of the crank-shaft can be found from the ram speed; this is generally from 60 to 100 ft. per min.

Revs. per min. \times Stroke in ins. = Actual speed of ram.

The calculation of the actual power requirements of ram pumps is explained in § 768. In very small pumps the efficiency may be only 25 to 30 %, but for medium and large outputs the efficiency is 50 to 60 % for a head of about 50 ft., and 70 to 80 % for heads of 150 ft. and over. The ram pump is specially suitable for small deliveries against a high pressure or head.

Unless relief valves are provided to by-pass some of the water, full-load torque is required throughout the period of starting; indeed, at the actual moment of starting, from $1\frac{1}{2}$ to $2\frac{1}{2}$ times full-load torque is needed to overcome the inertia of the column of water to be started in motion, and the static friction in the glands, etc.

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Cumulatively-compounded D.C. motors or wound-rotor A.C. induction motors are generally employed; squirrel-cage motors may be used for small pumps requiring up to 5 H.P. or so. These remarks apply also to pumps of the rotary piston, sliding-vane type, except that the torque required at the moment of starting is lower (say 60 % of full-load torque), owing to the smaller static friction.

770. Centrifugal Pumps.—In calculations relating to *centrifugal and turbine pumps* Duncan and Penman give the following formulæ:—

Let S = speed of periphery of impeller wheel, in ft. per sec.

H = vertical height in ft., or 'head' of water.

D = diameter of wheel in ft.

G = gallons of water per min.

R = revolutions per min.

Then $S = c\sqrt{H}$, where c is a coefficient of 8.2 for small and 9.8 for large pumps.

$D = \sqrt{(G / \sqrt{H})}$.

$R = 156 \sqrt{(H / D)}$ for small pumps.

$= 186 \sqrt{(H / D)}$ for large pumps.

Within the limits of the available driving power (motor H.P.) a plunger pump will deliver against any head; in fact, it *must* do so, the water being incompressible and the action of the pump being positive. On the other hand, there is for every centrifugal pump a definite maximum delivery-head, depending upon the design, which can only be increased by increasing the speed of the motor. Care must be taken, therefore, that the motor is capable of attaining the desired speed while developing the necessary horsepower. As will be seen from the formulæ above, the head against which a centrifugal pump can deliver water varies, theoretically, with the square of the r.p.m.; actually, the head increases less rapidly owing to the greater friction at higher speeds.

Provided that the delivery-head of the pump is not reduced below the value required, the output of a centrifugal pump may be regulated economically by varying its speed. If the discharge be throttled, the head is maintained, but this is an inefficient method of regulating the output. For example, from 65 to 75 % of the full-load H.P. is required when the output is reduced to zero by throttling the discharge, but this expenditure of power is sufficient to maintain about 85 % of the normal (full-speed)

delivery at about 82 % of the normal head if the speed be reduced to about 90 % of normal. If the pump be run at 60 % of normal speed, about 35 % of normal delivery is obtained at 40 to 45 % of normal head, and the power consumption is only about 20 % of the normal full-load value.

At constant speed (r.p.m.) a centrifugal pump generally delivers a greater quantity of water if the head is reduced, the exact shape of the head-delivery curve varying with the design of the pump. One consequence of this is that, if the head (useful or frictional) be increased, the delivery at constant speed is decreased, thus compensating more or less completely for the higher power consumed per gallon actually delivered. In the case of plunger pumps, on the other hand, the delivery necessarily remains constant at constant speed, regardless of the head, hence any increase in the latter places a correspondingly higher load on the driving motor.

The choice of motor H.P. for a centrifugal pump is affected considerably by the form of the head-delivery characteristic of the latter. Typical curves, plotted against the percentage of normal (rated) delivery, are given in Fig. 386; these must be accepted only as a general guide. If the head-delivery curve droops only slowly beyond the point of normal delivery, so that the delivery increases greatly when the head is reduced, the power absorbed at constant speed (*e.g.* when a D.C. shunt or A.C. synchronous or induction motor is used) rises greatly if the delivery-head is less than normal.* In such cases the pump must be 'over-motored,' and the motor efficiency is relatively low at normal pump delivery. If a D.C. cumulative-compound motor is used, the speed decrease on overload limits the latter by reducing the pump delivery. Similarly, if the head-delivery curve be steep, a decrease in head increases the delivery to such a small extent that the load on the motor may be actually reduced. Under such conditions the motor may be rated for the normal full-load, and a high average efficiency should be maintained. It is desirable, however, always to choose

* Apart from the rise in load due to the increase in the product: delivery \times head, the pump efficiency is low, owing to the frictional resistance of the large volume of water flowing through the pump. The power consumption can be restored to normal either by reducing the motor speed or by throttling the discharge, so as to restore the total head to its normal value; which is the more economical method depends on circumstances, especially the losses involved in reducing the motor speed.

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motors liberally for driving small centrifugal pumps, otherwise a little extra friction at the glands may seriously overload these small high-speed machines.

Attention may here be drawn to the note below Table 143 (§ 764) dealing with the analogous case of centrifugal fans. It has been observed in actual estimates for large irrigation pumps that some manufacturers guarantee a far higher pump efficiency than

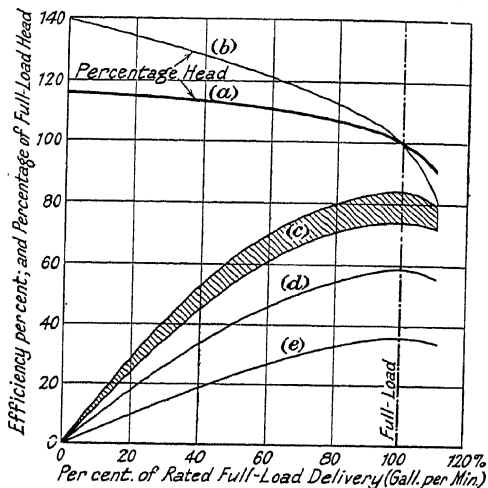


FIG. 386.—Characteristic curves for centrifugal pumps at constant speed.

- (a) Normal head-delivery curve.
- (b) Steep head-delivery curve; delivery nearly constant though head varies considerably.
- (c) Range of efficiencies for high-flow, medium-head centrifugal pumps; e.g. 3 000-20 000 gallons per min., 50-150 ft. head.
- (d) Typical efficiency curve for small-flow, high-head centrifugal pump; e.g. 200-500 gallons per min., 500-1 500 ft. head.
- (e) Typical efficiency curve for small centrifugal pumps as used for domestic service.

others, but that the H.P. of the motor involved proves the same in both cases, or may even be greater for the nominally more efficient pump. The explanation of this anomaly lies in the fact that static head alone has been taken into account in calculating the efficiency in the one case, while the velocity head is also included (as it should always be) in the other. In a particular case the efficiencies claimed differed by about 15 %, but the power required was identical.

As the delivery of a centrifugal pump depends upon the head

to be overcome and the speed at which the pump is driven, the effect of a change in speed upon the H.P. consumed can only be determined by reference to the characteristic curves of the pump.

For example, suppose that the characteristic curves are as shown solid in Fig. 387, the normal conditions being 2 000 gallons per min. delivered against 150 ft. total head by a power expenditure of 120 H.P. at 1 000 r.p.m.* Curve *a* represents the pump head plotted against the delivery, while curve *b* represents the 'system head' (= static head *plus* frictional head) plotted against delivery. The pump evidently operates at the point *A* where the pump head equals the system head.

If the pump speed be increased to 1 100 r.p.m. the head becomes about $150 \times (1\,100 / 1\,000)^2$ or 182 ft., and the delivery about $2\,000 \times 1\,100 / 1\,000$ or 2 200 gallons per min. Plotting 182 ft. against 2 200 gallons per min., we obtain *A'*.

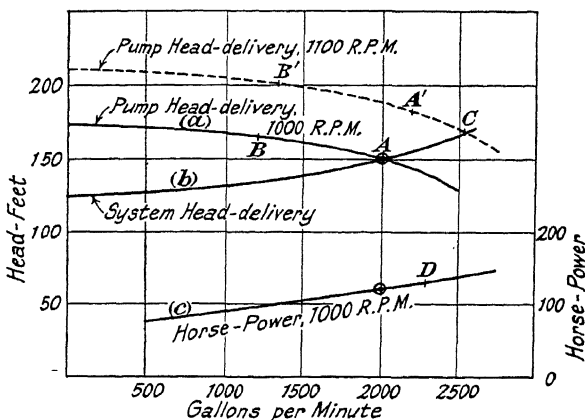


FIG. 387.—Illustrating estimation of centrifugal pump head, delivery and H.P. at different speeds.

Similarly, *B* gives *B'* at 1 100 r.p.m., and so on. The system head-delivery curve remains unaltered, hence the pump now operates at *C*, corresponding to about 2 530 gallons per min. and 168 ft. head.

The power now consumed can be estimated roughly as follows: A delivery of 2 530 gallons per min. at 1 100 r.p.m. corresponds to $2\,530 \times 1\,000 / 1\,100$ or 2 300 gallons per min. at 1 000 r.p.m., requiring 130 H.P. (point *D*, curve *c*). Hence the power at 1 100 r.p.m. will be $130 \times (1\,100 / 1\,000)^3$ or about 173 H.P.

* If only these data were known the complete head-delivery curve and H.P. curve could be calculated, with sufficient accuracy for the purposes of general estimates, by means of the percentage curves shown in Fig. 386. Thus, from Fig. 386, at 40 % of normal delivery, the head is 1.13 times normal (curve *a*), and the efficiency is about 46 %. Hence in the present case, at $0.4 \times 2\,000 = 800$ gallons per min., the head is $1.13 \times 150 = 170$ ft., and the H.P. is $(800 \times 10 \times 170 / 33\,000 \times 0.46)$ or about 90 H.P., which agrees reasonably well with Fig. 387.

For driving centrifugal pumps at constant speed, A.C. synchronous or induction motors may be employed. If speed variation be desired, the D.C. shunt-wound motor is more suitable and, by adding about 10 % of series field ampere-turns (cumulative compounding), a drooping speed characteristic is obtained which tends automatically to restrict the overload on the motor. The starting torque required by centrifugal pumps is usually from 20 to 30 % of full-load torque, rising to full-load torque at full speed with the discharge open and 50 to 60 % of full-load torque at full-speed with the discharge closed.

771. Propeller or Screw-Type Pumps.—Pumps of this type are used to raise large volumes of water against low heads for drainage or irrigation purposes. A shaft extending through the back of a 135-degree (approx.) pipe bend carries an impeller in one mouth of the bend (the discharge outlet), the other end forming the suction intake. The shaft may be driven by a direct-coupled synchronous motor of the flywheel type where low speeds are required for high-capacity pumps; smaller pumps may be direct-coupled to induction motors or synchronous-asynchronous motors. The whole of the interior of the pump, including the discharge, is usually under a partial vacuum during operation. The pump may be started light, and then 'primed' or filled by a small auxiliary vacuum pump after it is up to speed. Propeller pumps are usually more efficient than centrifugal pumps for any head below 12 ft., provided that the amount of water to be dealt with exceeds about 10 000 gallons per min. Pumps of this type, 12 ft. in diameter, driven at 83 r.p.m., are used in New Orleans to pump from 225 000 to 300 000 gallons of water per min. against heads ranging from zero up to 12 ft. Smaller pumps, down to 24 or 30 ins. diameter, are in use at 250 to 350 r.p.m., pumping about 8 000 gallons per min. against heads of 5 to 10 ft. A possible application for such pumps is in circulating water through large steam condensers.*

772. Hydraulic Rams.—That much-neglected device, the hydraulic ram, has possible uses in connection with water power. Water-hammer, which is a constant source of danger in ordinary hydraulic work, gives the motive power in a ram. If a supply of

* See 'Propeller Pumps for Condenser Service,' by R. K. Annis, *Power*, Dec. 27, 1927, p. 1002.

water is flowing from a higher to a lower elevation in a pipe, and if the flow is instantaneously arrested, the theoretical rise of pressure in lb. per sq. in. is $63\frac{1}{2}$ times the velocity in ft. per sec. (§ 248, Vol. 1). A suitable waste valve is provided at the foot of the pipe through which the water can escape; but it is so designed that when the velocity of the water issuing through it reaches its maximum value it is suddenly closed by the current acting upon it. A delivery pipe, reduced in size, is carried on to the higher elevation to which it is desired to force a proportion of the water. Near the junction, beyond the waste valve, an air vessel is placed in the pipe with a non-return valve. The suddenly applied pressure, as the waste valve closes, forces some water into the air vessel, until the available energy is exhausted, and the compressed air expands as its non-return valve closes, and forces this water up the supply pipe. The cycle of operations is automatically and rapidly repeated, and practically no attention is required when once the ram is fitted up. A long supply pipe, *i.e.* a long moving column of water, is obviously advantageous; so is a short delivery pipe, with reduced friction losses. The efficiency, *i.e.* $(\text{Flow delivered} \times \text{rise in feet}) / (\text{Total flow} \times \text{fall in feet})$, is a very variable quantity, depending largely on the relation of the driving head to the lift, and may vary from 20 % with high lifts up to 90 % or more on low lifts. It is possible to lift a small proportion of the water (about $1 / 100$ of the total) up to twenty times the height of the original fall. It is recorded* that a hydraulic ram with a power head of 50 ft. and a lift of 140 ft. discharged from 720 000 to 1 300 000 gallons a day with an efficiency of 85 to 90 %. With such capacities the ram becomes more than a device for supplying country houses with water and may serve its purpose as an auxiliary in a power scheme, as shown in § 230A, Vol. 1 (5th edition). With large quantities of water the main difficulty is found in the violence of the reaction when the waste valve closes; this, however, is being brought under control.

A device, based on entirely different principles, but with the same function of lifting water automatically by means of the energy of a fall, is known as the Hydraulomat (§ 230 (2)); and this has even greater possibilities as an auxiliary in a power scheme as well as for unattended irrigation from canal falls. In this,

* *Eng. News Record*, May 23, 1918, p. 1000.

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gradual air compression and release is used in place of water-hammer, and the action is free from shock. The efficiency, except on very low falls, is higher than that of a ram.

773. Refrigerating Machines.—Legislation now in force in this country prohibits the use of preservative materials which were formerly employed in various foods. There has consequently arisen a greater need for refrigerators, not only in warehouses and shops but also in private houses. Cold storage as a means of preserving meat, fruit and other perishable foodstuffs during its transport over long distances has been a standard part of the equipment of ships for many years past. Without it, the present concentration of population in cities and in industrial pursuits would be impossible; the standard of living in most countries would be reduced, and it is doubtful whether the present population of this and other densely populated industrial countries could be supported. The successful preservation of foodstuffs for comparatively long periods in ships and warehouses demands the maintenance of temperatures (different for different foods) constant within 1° F. or so; and brine circulation is necessary in all but small cold stores (less than 1 000 cu. ft.) in order to maintain uniform temperature; in most instances, also, close attention is required to the ventilation of the cold store. These are matters which demand the attention of the expert in refrigeration; the electrical engineer's share in the problem is confined to supplying motors for the compressors, circulating pumps, fans, etc., maintaining a reliable source of electricity supply, and installing thermostatic control gear and transmitting or recording thermometers.

Refrigerating equipment for private houses, hotels, restaurants, and shops, where raw or cooked food is to be kept for a comparatively short period (usually a day or two), falls under a different heading. Here the problem is to maintain a temperature low enough to take the place of chemical preservatives in preventing the rapid deterioration of perishables, yet not so low as to render the food unfit for immediate consumption. Generally a cupboard or cupboards, lined with cork or similar heat-insulating material, is kept at about 40° to 45° F.* by the circulation of air which is

* Most of the bacteria which attack fresh food are inert at temperatures below about 45° F., but very active at temperatures above 50° F. In order to be effective, the refrigerator must keep the food at a temperature not exceeding 40° to 45° F.

cooled by the refrigerating machine. The capacity of this storage space may be 5 to 15 cu. ft. in a domestic equipment and 50 to 250 cu. ft. in models designed for hotels, dairies, hospitals, and so on. A small inner compartment kept at lower temperature and used for quick cooling is a convenience; and arrangements are generally provided for making a limited quantity of ice in the form of small blocks by freezing water in trays.

Table 149 shows leading particulars of a number of British electrical refrigerators on the market during recent years. For small storage capacities, up to 45 cu. ft. or so, the continuous absorption machine offers the advantages of lower first cost, compactness and simpler maintenance owing to the absence of motor, compressor and other moving parts; its average electrical consumption, however, is somewhat higher than that of motor-driven compressor refrigerators.* When selecting refrigerators, attention should be paid to the quantity of water (if any) required for cooling. In most places an extra charge is made for water used for such purposes, up to £1 or so per annum for domestic refrigerators, and by meter for commercial refrigerators. According to the size of the refrigerator and the temperature of the atmosphere, from 3 to 4 kWh per diem may be required to operate a small domestic refrigerator cabinet.

There is already a large demand for electrical refrigerators for use by tradesmen, and this demand will extend because refrigeration now offers the only permissible means of preserving perishable foodstuffs, quantities of which must be kept in stock. Small electric refrigerators for domestic use would be adopted more widely if the first cost of the equipment were materially reduced. It may be argued that there is already an enormous number of these appliances in use in the U.S.A. but, apart from the different spending powers of the two countries, it seems to be forgotten

To provide for the rapid absorption of heat from fresh food, and for drying the air in the cabinet by freezing out moisture, the cold-producing part of the refrigerator is usually at 30° F. or a lower temperature.

* At 1d. per kWh, 100 W saved on the *average continuous* (24-hr.) electrical consumption represents $\frac{100 \times 24 \times 365}{1000} = 876d.$ or £3 13s. per annum, corresponding to 5% on £73 investment. In other words, it is worth while to pay up to £73 more for a machine which saves 100 W continuously; or £36 10s. extra if the machine is used only 6 months per annum; and so on. If electricity costs more than 1d. a unit, the capital value of 100 W saving on the power consumption is correspondingly increased.

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that the climate of the United States is very different from our own.* The average English household has rarely more than two days' supply of the more perishable foods in its larder, and there are few days in the year when this supply goes bad before it is consumed. Refrigerators are undoubtedly desirable on hygienic

TABLE 149.—*Typical Low-Power Electrical Refrigerators.*

Maker.	Net Storage Capacity. Cu. Ft.	Shelf Area. Sq. Ft.	Approximate Overall Dimensions. Height × Depth × Width.	Weight of Refrigerator Complete. Lb.	Motor.	Refrigerant.	Cooling.	Control.
A	4½ 7½ 10	5½ 7½ 15½	3'11½" × 1'9½" × 2'2½" 5'2½" × 1'9" × 2'11½" 5'10½" × 1'10½" × 3'3½"	320 350 380	½ H.P.; 1 cylr. ½ H.P.; 1 cylr. ½ H.P.; 1 cylr.	Methyl chloride	—	Automatic thermostat
B	6 10 45	10 — —	2'9½" × 2'0½" × 3'6½" — —	345 — —	No motor, 180- 360 W heating element			
C	9	13½	5'10" × 2'1½" × 3'2½"	896	½ H.P.; 2 cylr.	Sulphur dioxide	Air	Automatic thermostat
D	150-330	—	—	—	½ H.P.; 2 cylr.	Methyl chloride	Water	Automatic thermostat
E	11	12	6'0" × 2'4" × 2'9"	952	½ H.P.	Sulphur dioxide	Water	Hand (non-automatic)
F	5	7½ or 10½	5'2" × 1'6½" × 2'2½"	400	166 W	Sulphur dioxide	Air	Automatic thermostat

grounds and for convenience, but they are apt to be regarded as a dispensable luxury. In some blocks of flats and similar buildings, 'central refrigeration' is provided by a high-power refrigerator in the basement connected to cold storage cabinets throughout the building by lagged brine-circulating pipes. Though no operating

*New York is on the latitude of Madrid, and New Orleans on that of Cairo. Also, the U.S.A. is subject to Continental extremes of climate which do not occur in an island.

data regarding such plant appear to have been published at the time of writing, the system is obviously convenient and probably more economical than the equivalent number of independent refrigerators.

From the central station standpoint the use of refrigerating plant is well worth encouraging. The demand is fairly uniformly distributed throughout the twenty-four hours and is of substantial magnitude in the case of commercial cold stores and ice-making plants; even small domestic refrigerators consume from 300 to 1 500 kWh per annum, according to the use made of them, and thus compares well with the consumption for lighting purposes (§§ 576, 607, Vol. 2).*

Compressors for commercial refrigerating plant are usually driven by synchronous motors either directly or (the compressors being low-speed machines) through belting, sometimes with Lenix pulleys.

A certain 135-ton compressor was driven by a 550 H.P., 150 r.p.m. motor, and a 225-ton compressor by a 650 H.P., 164 r.p.m. motor. In large plants making 1 000 tons of ice per day the power for the ammonia compressors is about 8.8 H.P. per ton of refrigeration.

A 135-ton compressor is one capable of 135 tons of refrigeration per day. The term 'ton of refrigeration' means refrigerating duty equal to the freezing of 1 ton of ice per 24 hrs. The heat extraction needed to freeze

1 ton (2 240 lb.) of ice per 24 hrs., from and at 32° F.,
 $= 2\,240 \times 144 = 322\,560$ B.Th.U. per 24 hrs.
 $= 13\,440$ B.Th.U. per hr.

1 short ton (2 000 lb.) of ice per 24 hrs., from and at 32° F.,
 $= 2\,000 \times 144 = 288\,000$ B.Th.U. per 24 hrs.
 $= 12\,000$ B.Th.U. per hr.

If the raw water is at 60° F., the heat to be extracted to reduce it to 32° F. preparatory to freezing is 60 - 32 or 28 B.Th.U. per lb.

In temperate climates, using CO₂ refrigerators and working 24 hrs. a day, the outputs shown in Table 150 may be expected.

TABLE 150.—*Power Requirements of CO₂ Refrigerators.*

Motor H.P.	Ice per 24 hrs.	Storage at 30° F.
H.P.	Gwt.	Cu. ft.
1	2	100
2	5	300
5	20	2 000
10	40	5 000
20	90	14 000

* The latest available information concerning the development of the refrigeration load may be obtained from the Electrical Development Association, 15 Savoy Street, London, W.C. 2.

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In hot climates the output of ice and the storage at 30° F. may be taken to be 15 to 20 % smaller than these figures. Ammonia plants require less power than CO₂ machines.

An average expenditure of from 50 kWh to 60 kWh is required to produce 1 ton of ice by means of a motor-driven ammonia-compression system. The maximum demand of such an outfit reaches about 2·3 kW per ton of ice-making capacity. Of this demand about 1·5 kW per ton is due to the compressor itself, the remainder representing the work of the auxiliary apparatus. These figures represent the conclusions reached by a large central-station company after a study of a number of ice-making plants where electrical energy is used in motor-driven compressors. An energy consumption of 40-45 kWh per ton of ice is quite usual and 21 kWh per ton is sometimes reached in winter in the United States.

774. Portable Tools.—Almost every kind of tool is now available with a direct-coupled or geared electric motor forming a self-contained unit with a trailing cable which can be plugged into the nearest supply socket. Standard plugs and sockets should be used throughout, with first-class cables and switchgear, and an earthing lead. Either D.C., single or polyphase A.C., or 'universal' (D.C. and A.C.) motors can be used. For lightness and cheapness high-speed motors are used so that, except in the case of grinders, wood-working machines, and the like, reduction gearing is generally required between the motor and the tool spindle. D.C. motors for portable tools are generally series or compound wound; A.C. motors are usually of the 3-phase, squirrel-cage induction type; and 'universal' motors have series characteristics. It is sometimes recommended that 50 V or lower voltage of supply be used in order to reduce the danger of shock, but low voltage involves heavy machines and cables. Given proper construction and an earthing lead connected to the motor frame, there is no appreciable risk in using the standard industrial voltages for the motors concerned.

The smaller sizes of portable electric drills were originally, and are still sometimes driven by D.C. series motors. The 'free' speed of the latter is kept in check by the frictional resistance of the reduction gearing, etc., and by windage on the rotating parts, but it is still very high (up to 15 000 r.p.m. and even higher in very small machines). In common with all series motors, the speed decreases as the load increases and, at the normal output of the tool, it may be only half the 'free' speed. A possible objection to series motors in powerful tools is that the torque developed when the tool binds or seizes may tear the machine from the user's grasp. Larger portable tools are often driven by D.C. compound-wound

motors, the free speed being then limited by the shunt winding, while the series field produces a decrease in speed with increasing load, greater than that of the plain shunt motor but not so great as that of the plain series motor. 'Universal' motors, capable of operating at about the same speed on either D.C. or single-phase A.C. of the same voltage, are series-wound and have the same load-speed characteristic as ordinary D.C. series motors.

A.C. induction motors for driving portable tools offer the advantages that their free speed is definitely limited to a value just under the synchronous speed (§ 681), and that the decrease in speed on load does not exceed from 5 to 10 %. As a consequence, a greater maximum H.P. can be obtained from a rotor of given size and free speed. Also, better performance can be obtained from such tools as grinding wheels, for the latter can be used in economical sizes and at the most efficient full-load speed without dangerous racing on light loads. Similarly, the maintained speed on load increases the output and prolongs the life of metal-cutting tools. The maximum synchronous speed of a 50-cycle induction motor is, however, 3 000 r.p.m., hence a tool using such a motor is heavy compared with one embodying a universal motor with a free speed of 8 000 r.p.m. or so. In order to overcome this drawback '*high frequency*' induction motors are now often used. These are supplied by a motor-generator set or by a frequency-converter* delivering A.C. at higher than commercial frequencies. It is found that 180 cycles per sec. is about the most economical frequency; if a higher frequency be used the extra weight of the reduction gearing and the additional care required in lubrication and maintenance offset the extra saving on the weight of the motor itself. The synchronous speed of a 2-pole, 180-cycle motor is 10 800 r.p.m., and the speed at full load is about 9 940-9 720 r.p.m., corresponding to 8-10 % slip. This is a higher full-load speed than can be obtained with a D.C. or universal motor and, in consequence of the maintenance of speed on load, the maximum H.P. developed is much higher than with D.C. or universal motors. This point is well illustrated by Fig. 388,† which compares four electric grinders,

* Essentially a slip-ring motor the rotor of which is driven backwards by another motor so that the frequency of the 'slip' current exceeds the frequency of the primary supply.

† From '*High-Frequency Portable Tools and Equipment*,' by C. B. Coates, *Jour. Amer. I.E.E.*, Vol. 48, p. 521.

all of the same weight, driven by : (A) Universal motor geared down about 3 : 1. The spindle or arbor runs at 5 200 r.p.m. on no-load and at 2 000 r.p.m. when developing a maximum of 0.63 H.P. (B) Geared D.C. compound motor. The free speed of the spindle is now 4 400 r.p.m. and 0.81 H.P. is developed at 2 400 r.p.m. (C) Direct-coupled (gearless), 2-pole, 60-cycle induction motor. The free speed is just below the synchronous speed of 3 600 r.p.m., and 0.8 H.P. is developed at 3 200 r.p.m. (D) A 2-pole, 180-cycle induction motor is geared down about 3 : 1. The free speed is 3 800 r.p.m. and no less than 2 H.P. is developed at 3 200 r.p.m. spindle speed.

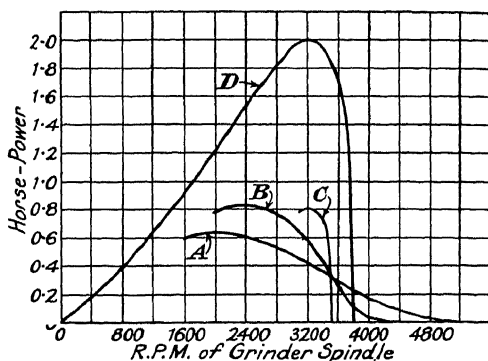


FIG. 388.—Comparison between different types of electric grinders.

- (A) With geared universal motor. (B) With geared D.C. compound motor.
(C) With gearless 60-cycle induction motor. (D) With geared 180-cycle induction motor.

Besides the use of electric motors for driving portable drills, saw, grinders, etc., there is a large field for their application to slow-speed tools such as screw-drivers. In the case of screw-drivers, a slipping clutch should be provided to limit the maximum torque applied. Screw-cutting, reaming, and similar machines are simply 'drills' geared down to about 30-60 r.p.m.; the power absorbed is generally from 250 to 1 250 W.

775. Machine Tools; Wood-Working Machines; Leather Machinery.—The type of motors generally used for driving machine tools are: D.C. shunt or compound motors with speed control by field-variation; 3-phase induction motors, speed variation then being provided by change-speed gears in the machine itself, and 3-phase commutator motors, with shunt characteristics and

speed control by brush displacement. The cost of power for driving machine tools is generally from 2 to 4 % of the total production cost of the work handled, a sum small enough to make it foolish to stint the power, but large enough to justify the careful avoidance of waste. Manufacturers' statements of the power requirements of machine tools are apt to be under-estimated; generally it is economical to provide an excess of power or, at least, the maximum power that can be required under the most unfavourable circumstances. Over-motoring results in low average P.F. where induc-

TABLE 151.—*Approximate Power Requirements of Machine Tools.*

	H.P.		H.P.
Lathes—		Shapers, 18-in. to 30-in. stroke	2-4
Screw-cutting, up to 6-in. centres	$\frac{1}{2}$ -1	Planers, 6 x 2 x 2 ft.	3-5
" 12-in. " 30-in. "	2-5	" 12 x 5 x 5 " "	10-15
Engine, 60-in. " 84-in. "	5-10	" 24 x 12 x 12 " "	40
Face, 5 ft. faceplate	2-3	(double head)	
" 10-ft. "	5-10	Punches, medium . . .	2-6
Turret . . .	2-4	Shears . . .	7-15
Drills—		Cold saws, 12-in. to 24-in.	2-5
Portable . . .		Hot saw ('cutting,' mainly	
Small sensitive		by frictional heat, 12-in	
Vertical . . .		channel iron in 30 secs.).	25-30
Radial, 4 ft. to 6 ft.	2-4	Bending rolls . . .	3-20
Boring mills—		Riveting machines . . .	3
3 ft. to 9 ft. . .	5-10	Countersinking machines	3 $\frac{1}{2}$
Vertical . . .	2-8	Grindstones . . .	1 $\frac{1}{2}$ -3
Milling machines—		High-speed abrasive wheels—	
Small . . .	$\frac{1}{2}$ -1	Up to 12 ins. diameter	$\frac{1}{2}$ -1
Medium universal	2-4	18 ins. to 30 ins. diameter	2-3
Heavy . . .	5-15	Forge fan, 24 fires . . .	10
Slotters, 12-in. to 24-in. stroke	5-10		

tion motors are used, but this can be corrected (Chap. 5, Vol. 1), and it is better to incur the cost of P.F.-correction, or some increase in the cost of energy supply (§ 274, Vol. 1), than to restrict the capabilities of a machine by providing inadequate motor H.P. Where feasible, the metering of similar machines in actual service provides the best guides to the H.P. required.

For information relating to the use of magnetic chucks see § 807.

The figures in Table 151 assume the use of such steels and speeds as are employed in average workshops. Higher power may be required where special tool-steels are worked to the limit of their

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capacity, and considerably lower power is sufficient in many cases if ordinary carbon tool-steels be employed.

The remarks made above, concerning the advisability of adequate motor power, are specially applicable to wood-working machinery,

TABLE 152.—*Approximate Power Requirements of Wood-Working Machinery.*

	H.P.		H.P.
Saws—		General joiners . . .	4-6
Circular 24 ins. diameter	5-10	Mortising machines—	
" 48 " "	25-35	Light	2-4
" 60 " "	40-50	Heavy	10-15
" 30 " cutting 16-in pine	14	Chain mortisers . . .	4-8
" 43 " cutting 18-in teak	24	Tenoning machines . .	5-10
Band, hand feed	2-5	Boring machines . . .	8-15
" heavy logs	20-40	Moulders	3-8
Rip, 6-in. hardwood	15	Pattern-makers' lathes	2-3
Fret, up to 8 ins. depth of cut	1-2	Flooring machines . .	10
Frame	25-50	Gaining machines . .	15
Cross-cut, small . . .	2-5	Sandpaper machines .	2-4
" heavy	15-20	Saw-sharpening machines	1-1½
Planers, small	1-3	Moulding iron girders .	1-1½
" high-power . . .	10-15		

owing to the frequent occurrence of wet wood, hard spots, etc. The advantages of high-speed blades cannot be realised unless the motor power is sufficient to maintain full speed under all conditions.

TABLE 153.—*Approximate Power Requirements of Leather-preparing and Boot-making Machinery.*

	H.P.		H.P.
Bark breakers (5 to 10 tons per day)	5-10	Clicking presses, peggers, sole	
Tan presses	2-3	levellers, heel fixers, scourers,	
Hide cleaners and rollers, light	1-3	finishers, name stampers, etc.	½-1
" heavy	5-10	Screwdrivers, heel crushers, trim-	
Bootmakers' presses and rollers	½-1	mers, pounders, bottom	
Stampers, skivers, splitters, round		scourers, finishing machines,	
ers, perforators, eyeletters, chan-		etc.	1-2
nelers, trimmers, sewers, etc.	¼-½		

The light-load power consumption of wood-working machinery may be taken to be from $\frac{1}{2}$ to $\frac{1}{3}$ the full-load power (shown in Table 152) for planers, mortisers, tenoning and boring machines, and general joiners, and from $\frac{1}{4}$ to $\frac{1}{2}$ the full-load power in the case of circular saws.

There are many leather dressing and tanning processes now in use, and a corresponding diversity in the machinery employed and in its power consumption. Table 153 includes a few typical figures bearing on this industry and on the power consumption of machinery used in boot factories.

776. Textile Machinery.—Every case for electric driving in textile mills has to be considered on its merits. There will be cases where it is obviously best to put in a group drive, *e.g.* in old mills, where existing machinery cannot be altered; but wherever it is found possible to adopt the individual drive this method, together with a few well-chosen group-driving motors, is undoubtedly preferable. The supply is generally 3-phase A.C., 50-cycles, 230 V, where individual loom motors are used; for the larger motors a higher voltage may conveniently be used. The uniformity of turning moment with individual driving enables a higher speed to be used, giving a greater output and better quality; the tension on belts is easily adjusted to give the smoothest running; starting and stopping by the switch is readily performed; dust and dirt are lessened, and with them repairs to the looms. The machinery can be placed in the most suitable position without having to take into consideration such questions as large rope and belt pulleys, shafting, etc. It is not necessary to run the whole mill to operate a few machines. The actual power taken by any machine can be measured, and this enables the engineer to see that each is working at its best. On the other hand, the P.F. is low where many fractional-H.P. motors are used unless these are of a 'compensated' type. In a certain case where several hundred small induction motors were used for the individual driving of looms, the average P.F. of the installation was 0.35-0.4. Compensated motors are now available, designed specially for the driving of looms; and, if necessary, central apparatus can be installed for P.F.-correction (Chap. 5, Vol. 1).

The relative prospects for purchased power and private generating plant in textile works depend largely on the demand for 'process' steam in the manufacturing operations. In woollen and worsted mills and to an even greater extent in dyeing and finishing works, the demand for process steam is high, and all the power required can be developed by back-pressure engines or turbines exhausting into the process mains; the power is then obtained as a by-product at costs with which no central station can compete (§§ 176, 188, Vol. 1). In cotton mills, on the other hand, there is little use for

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exhaust steam, hence a private steam-driven generating plant can hardly compete with supply from a large modern central station. Even in such cases, however, Diesel-driven generators often make private generation more economical than purchased supply.

TABLE 154.—*Power Required to Drive Cotton-Spinning Machinery.*

No allowance is made for starting torque and frictional losses; see text.

	H.P.		H.P.
Single-acting Macarthy gin		Sliver lap machine	1
Double-acting Macarthy gin		Ribbon lap machine (draw and lap machine combined)	1
Bale breaker		Comber, single nip, 6 heads	
Willow		" " " " 8 "	
Small porcupine opener		" double " 6 "	
Automatic hopper feeder		" " " " 8 "	
Vertical beater opener, single Crighton		Bundling press	
Vertical beater opener, double Crighton		Banding machine	
Exhaust opener		Tubular banding machine, 3 heads	3
Single opener (without hopper feeder)		Tubular banding machine, 6 heads	6
Double opener (without hopper feeder)		Balling machine, per head	
Single scutcher		Plain calico looms (3 to 4 machines)	4
Double scutcher		Hydraulic cloth press	
Card, revolving flat			

Frames, etc.

	Per H.P.		Per H.P.
Draw frame; deliveries	12	Twinner, French principle; spindles	140
Slubbing frame; spindles	90	Quick traverse winding frame; drums	80
Intermediate frame; spindles	130	Ordinary winding frame; spindles	300
Roving frame; spindles	160	Gassing frame; drums	80
Jack frame; spindles	200	Reel (Coleby's); reels	6
Mule, Indian and American cotton; spindles	120	Improved reel (for gassed yarns); reels	8
Mule, Egyptian and Sea Island cotton; spindles	130	Single ordinary reel; reels	16
Ring-spinning frame; spindles	100	Double ordinary reel; reels	8
Ring-doubling frame; spindles	60	Copping frame; spindles	300
Twinner, Yorkshire principle; spindles	200		

Cotton Spinning and Weaving.—Table 154, reproduced by courtesy of Thomas Broadbent & Sons, Ltd., Huddersfield, gives typical data concerning the power required to drive cotton-spinning machinery. These figures are for the actual H.P. required to run the machinery; to arrive at the H.P. required for individual

driving, add 25 % for frictional losses and 50 % for starting torque. For example, Table 154 shows that the net power to drive a 400-spindle ring-spinning frame is $4 \times 1 = 4$ H.P. Add 25 % = 1 H.P. for friction; and 50 % = 2 H.P. for starting torque; and the total = 7 H.P. A standard $7\frac{1}{2}$ H.P. motor would therefore be suitable.

The data in Table 155 are published by courtesy of Mr. G. Laird, General Manager for India of Associated Electrical Industries, Ltd. They give the speed and power required for individual drives in the weaving shed and finishing department of a modern cotton mill, including frictional losses, and are based on tests carried out in twenty-seven cotton mills electrified by the company.

TABLE 155.—*Power Required for Cotton Weaving and Finishing.*

	H.P.	R.P.M.		H.P.	R.P.M.
<i>Weaving.</i>			<i>Sizing Department.</i>		
Loom reed space, 28"-44"	$\frac{1}{2}$	960	Beam warpers, per row		
" " " 54"	$\frac{3}{4}$	960	of 6	5	575
" " " 78"	1	960	Sizing machines	6	—
			Size mixing becks	12	575
<i>Finishing Department.</i>			<i>Winding Department.</i>		
Humidifiers	35	710	Grey winders	3	575
Baling presses	10	710	Colour and pirn		
Cloth stampers	2	1 400	winders	$2\frac{1}{4}$	575
Cloth folders	1	960	Card-room machin-		
Spray dampers	5	475	ery	160	290
Mote clearers	5	475			
7-cowl calenders	75	365			

From various other sources Table 156 is added.

TABLE 156.—*Power Required for Cotton Spinning and Weaving Machinery.*

	H.P.		H.P.
Bale breakers	2-5	Reels	$1\frac{1}{8}$ - $\frac{1}{2}$
Openers	2-4	40 in. Lancashire looms (180-	
" " high-power	5-10	200 picks per min.)	$2\frac{1}{2}$ -4
Beaters	3-8	5 ft. sailcloth looms (60-120	
Scutchers	4-8	picks per min.)	1- $1\frac{1}{2}$
Carding engines	$\frac{1}{2}$ -1	Indian cotton mill looms	$\frac{1}{4}$ - $\frac{1}{2}$
Doublers	$\frac{1}{2}$ -1	Calico looms (3 to 9 ft. reed	
Sliver lap	$\frac{1}{2}$ -1	space)	$\frac{1}{2}$ - $2\frac{1}{2}$
Ribbon lap	$\frac{3}{4}$ -1	Cloth presses	$\frac{1}{2}$ -1
Combers	$\frac{1}{2}$ -1		

[Continued overleaf.]

TABLE 156.—(Continued.)

Frames, etc.

	Per H.P.		Per H.P.
Slubbing; spindles . . .	40-50	Doubling; spindles . . .	40-70
Intermediate; spindles . . .	55-60	Winders; spindles . . .	200-400
Roving; spindles . . .	65-80	„ drums . . .	80-120
Ring; spindles . . .	70-100	Wet winders; spindles . . .	120-150

Woollen and Worsted Machinery.—The figures in Table 157, reproduced by courtesy of Thomas Broadbent & Sons, Ltd.,

TABLE 157.—*Power Required to Drive Woollen and Worsted Machinery.*

No allowance is made for starting torque and frictional losses; see text.

	H.P.		H.P.
Wool drying machine . . .	15	68-in. raising gig . . .	5
Burr crushing machine . . .	4	72-in. double brushing machine . . .	6
Mule, 350 spindles \times 2½ pitch . . .	6	Steaming and cool air exhaust- ing machine . . .	10-12
Pirn winder, 40 spindles . . .	4	Single-dish rotary press . . .	3
Quick traverse cheese winder, 40 drums . . .	2	Double-dish rotary press . . .	5
Warping machine, 20-ft. arm \times 90-in. gauge . . .	1½	Two-piece rotary press . . .	5
Split drum winder, 40 drums . . .	2	Napping machine . . .	4
Warp sizing and drying machine . . .	7	Pump (2-plunger), 1½ in. diameter ram . . .	7-8
Waste cleaner . . .	½	Pump (3-plunger), 1½ in. diameter ram . . .	7-8
Twisting machine, 200 spindles . . .	6	Power-driven baling press . . .	7
Soaping machine . . .	1	48-in.-wide self-acting teaser . . .	15
Scouring machine (rope) . . .	6	48-in.-wide Fearnought or tender hook willow . . .	12
Scouring machine, open width . . .	4	Carding machine—complete large set comprising: hopper, scribbler scotch feed, con- denser, etc.	8
Milling and scouring machine . . .	6	60-in.-wide botany worsted carder	5
Milling machine (ordinary) . . .	6-7	Dobcross fast loom, 85 to 100 picks	¾-1
Milling machine (improved) with wide rollers 10 to 14 ins. wide, 18 ins. diameter . . .	10-15	Hattersley's standard loom, 105 picks	1
Milling machine for felts, with rollers 24 ins. wide \times 38 ins. diameter	20	Petries' chamber drying machine, no. 1 size, 6 bays . . .	12
Scouring machine (felts) . . .	9	Petries' chamber drying machine, no. 2 size, 5 bays . . .	8
Squeezing machine . . .	3	Petries' chamber drying machine, no. 3 size, 4 bays . . .	7
Hot air tentering machine, 12 layers, 3 bays	15	Broadbent's 72-in. electric hydro extractor	8
Improved tentering machine, 12 layers, 3 bays (Oochran's) . . .	7	Broadbent's 86-in. electric hydro extractor	3
Dewing machine	2		
Damping machine (for shrink- ing)	2		
Rag-cropping machine	1½		
Cloth-cutting machine (single, double, triple and quadruple) . . .	1-4		

Huddersfield, show the actual H.P. required to drive woollen and worsted machinery. To obtain the H.P. required for individual driving add 25 % for frictional losses and 50 % for starting torque; see example on Table 154.

Jute Mills.—The figures in Table 158, published by courtesy of Mr. G. Laird (*supra*), are average values for the power required to drive jute mill machinery, including fractional losses in shafts and belting. A safe average figure for the total power to be generated for a jute mill is 3 kW per loom. Generally, motors of 100 H.P. and over are of the slip-ring type; smaller machines may be of the squirrel-cage type.

TABLE 158.—*Power Required to Drive Jute Mill Machinery.*

H.P.		H.P.	
Softeners . .	16	Cutters .	2
Dust shakers . .	1	Dampers	1
Waste breakers . .	2½	Twist frames	8
Spools (double machine)	4	36 drawings	1½ H.P. each
Looms	¾	Rovings .	10 spindles per H.P.
Calenders, 64"-96"	8-10	Spinning frames	15
Press pumps . .	40		20
Laps	1	9 beaming machines	3 H.P., "including" dressing
Measurers . .	1	Sewing machines	6 to 8 per H.P.

One method of driving is to couple a motor directly into each lineshaft at the centre of its length, solid couplings being provided at each end of the motor. The motors are mounted on an iron framework fixed to the mill columns; and, as they are high up, a clear passage is provided beneath them, and they interfere in no way with the mill passes. Power being applied at the centre of the shafts, torsion of the latter is reduced to a minimum, and the shafts may be made lighter; also, there are no main ropes or pulleys, and the expense of a motor alleyway is saved. Though the above arrangement is considered best for a mill with more than 400 looms, it is found preferable in smaller mills to place the motors in a special alleyway.

777. Paper-Making and Printing Machinery.—The scale on which paper mills are operated, the nature of the raw materials and of the final product vary over so wide a range that the data in Table 159 may be taken only as indicating the general nature of the loads to be supplied in a large mill.

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Power requirements are heavy where a large tonnage of paper is made from wood-pulp. The principal loads in a newsprint mill are for handling, barking and grinding logs, pumping water and pulp, and driving the paper-making machines themselves. Full advantage should be taken of combined 'power and process' working (§ 176, Vol. 1) in every paper mill. In many machine-tool drives a small departure from the ideal speed is preferable to complication in control, but in the driving of paper machines absolutely continuous speed control is essential. Also, it is necessary to maintain an exact relation between the speeds of the various rolls (couch roll, press rolls, dryers, calender and reeler) in order that the paper

TABLE 159.—*Power Required to Drive Paper-Mill Machinery.*

	H.P.		H.P.
Guillotines (2 to 4 ft.).	1-4	Wet pulpers	25
Paper glazers	3-5	Press plates	30
Rulers .	5	Breakers	20-60
Elevators	5-10	Beaters .	20-100
Cutters .	5-10	Calenders	60-100
Fans .	5-15	Paper-making machines	25-50
Dampers	10		up to 100-200
Saws and barkers	10-20	Pulp crushers and refiners .	100-300
Coating machines	20	Pumps	5-200
Dusters and fans	25		

may be neither torn nor varied in thickness. On entering the wire the 'stuff' may be nearly 99 % water; after couching it still contains 75 % or more water; and even between the third press and the smoothing rolls the paper contains about 65 % moisture. Formerly, purely mechanical drives were used for paper machines, but various systems of sectional electric driving have been devised in which a separate motor is used for each section of the machine, an exact relation between the various speeds being maintained electrically without impeding the freedom and flexibility of speed control.* According to R. N. Norris (*loc. cit.*), the average of some hundreds of readings on various paper machines are as in Table 160.

From Table 160, a 234-in. machine operating at 1 000 ft. per min. would require 472 E.H.P. A mechanically operated machine at the same speed would need about

* For details of the mechanical and electrical requirements of paper-mill plant, see 'Modern Development of Paper-Mill Plant,' by W. Worby Beaumont and L. N. Burt, *Proc. Inst. Mech. Eng.*, 1926; and three papers by H. W. Rogers, R. N. Norris and S. A. Staage, *Proc. Amer. I.E.E.*, 1926.

519 E.H.P. If the machine output is 125 tons of paper per 24 hrs., and the drying of the paper requires 3.75 lb. steam per lb. of paper, the drying cylinders consume 38 900 lb. of steam per hr. A back-pressure turbine would generate about 1 000 E.H.P. from this quantity of steam, and the excess over the requirements of the sectional electric drive, viz. $1\ 000 - 472 = 528$ E.H.P., would generally be sufficient to drive the constant speed end of the paper machine, thus rendering the whole a self-contained unit.

The advantages of electric driving by individual motors are particularly great in printing works. The absence of lineshafts, belts, etc., facilitates good lighting, cleanliness, and unobstructed access to the machines; also, each of the latter can be driven at the best speed for the work in hand. The fact that most of the machines run independently of each other is a further argument in

TABLE 160.—*Power Required by Paper Machines.*

Width and Type of Machine.	Average Speed, Ft. per min.	Electric H.P. Input to Motor per inch width of Machine per 100 Ft. per Min. Paper Speed.								
		Couch.	1st Press.	2nd Press.	3rd Press.	Dryers.	1st Cal-ender.	2nd Cal-ender.	Exciter.	Total.
234-in. News	875	0.039	0.016	0.023	0.022	0.060	0.036	—	0.0057	0.2017
166-in. News	750	0.054	0.029	0.027	0.0	0.074	0.050	—	0.009	0.243
168-in. Kraft	675	0.039	0.027	0.020	0.017	0.041	0.036	—	0.008	0.188
148-in. Book	530	0.046	0.044	0.026	0.014	0.035	0.031	0.068	0.008	0.300
148-in. Tissue	230	0.017	0.041	0.017	—	0.047	0.048	—	0.006	0.171

favour of individual driving. Group driving by a constant-speed motor and lineshaft is sometimes used, to reduce the first costs of the installation, but individual driving will improve the output and reduce the electricity bill in even the smallest jobbing printing works. Considerable speed reduction is generally required between the motor and press shafts; this may be obtained by spur-gearing or, usually at lower cost, by toothed chain or Lenix belt drive.

In the case of the press itself provision has to be made for a steady 'creeping' speed (for use when making ready), and for a variation of the running speed (over a range of from $2\frac{1}{2}$ to 5:1) to suit the work in hand. Either shunt or compound-wound D.C. motors, or A.C. commutator motors with shunt characteristics, may be used; slip-ring induction motors may also be employed, but speed-regulation of these machines by rotor resistance is neither economical nor stable.

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High-speed rotary presses, for newspaper and similar work, are generally fitted with two motors. The main driving motor is either a D.C. compound-wound motor or a 3-phase A.C. commutator motor with a speed range of 3 or 4:1. A 'barring' motor, for 'inching' the press, consists of a D.C. compound or A.C. slip-ring induction motor driving the main motor shaft through a worm gear and 'freewheel' ratchet coupling. As soon as the main motor takes up the load, to accelerate the press to its normal running speed, the ratchet coupling puts the barring motor and worm gear out of

TABLE 161.—*Power Required to Drive Printing Machines.*

	H. P.	R. P. M.	Type of Motor.
Two-colour Miehle Perfector press	10	705	Slip-ring induction
Miehle press	6/2½	1200/500	3-ph. variable commutator
" " " " " " " " " " " "	6	700	Slip-ring induction
Voirin offset	2	600/1800	D.C. compound
Offset litho	2½	480/600	" " " " " " " " " " " "
Crabtree Rotary Printing press (newspaper)	70/17½	750/188	3-ph. variable-speed commutator
Barring motor	7½	—	—
3-deck 12-page Hoe rotary printing press	70/23	750/250	3-ph. variable-speed commutator
Barring motor	7½	—	—
Hoe press (weekly periodicals)	30/6	1100/220	3-ph. variable-speed commutator
Barring motor	3	—	slip-ring induction
4-deck Foster rotary press (newspaper)	55/18½	870/290	A.C. commutator
Barring motor	5	—	—
Crabtree rotary press (newspaper)	50	550/1100	D.C. compound
Barring motor	7½	1000	" "

action, and the barring motor is automatically disconnected from the supply.

Squirrel-cage induction motors are suitable for driving platens, guillotines, and other small machines running at constant speed and requiring only a moderate starting torque.

Automatic control gear, actuated by push-buttons duplicated at as many 'stations' as desired, is advisable on practically all printing presses. Its cost may appear to be prohibitively high where small presses are concerned, but even in such cases it safeguards the motor and press and increases the output to such an extent that it is a good investment. On high-speed presses, and presses engaged in special work demanding continual attention, automatic control gear is almost essential for best results. If there are long runs of

printing at constant speed, the speed may be adjusted manually, automatic press-button control being then restricted to starting, 'inching,' and stopping.

The figures in Table 161 are from various installations by the British Thomson-Houston Co., Ltd.

In connection with the data given in Table 162 concerning letterpress printing, it may be noted that a speed reduction of about 6 to 1 is usual with motor drive. There are about $3\frac{1}{2}$ revolutions of the shaft and flywheel to each printed sheet. A duplex 'offset' machine printing 10 000 sixteen-page papers per hr. in two or four colours requires two 20 H.P. motors.

TABLE 162.—*Power Required to Drive Printing Machines.*

	Maximum impressions per hour.	H.P.		Copies per hour.	H.P.
<i>Letterpress.</i>			<i>Newspaper Printing.</i>		
Demy ($22\frac{1}{2}" \times 17\frac{1}{2}"$) . . .	2 000	$1\frac{1}{2}$	4 pg. Hoe machine . . .	24 000	20
Double crown ($20" \times 30"$) . . .	1 800	2-3	8 " " " . . .	24 000	35
Double demy ($22\frac{1}{2}" \times 35"$) . . .	1 700	3-4	16 " " " . . .	24 000	60
Double royal ($25" \times 40"$) . . .	1 700	4-5	32 " " " . . .	24 000	120
Quad crown ($30" \times 40"$) . . .	1 600	5-6	10 " Webb perfecting . . .	12/24 000	15/30
Quad demy ($35" \times 45"$) . . .	1 500	5-8	12 " " " . . .	12/24 000	20/30
Quad royal ($40" \times 50"$) . . .	1 400	6-9	32 " " " . . .	12 000	30
<i>Lithograph.</i>			<i>Calico Printing.</i>		
Demy ($22\frac{1}{2}" \times 17\frac{1}{2}"$) . . .	900	2	Printing machines—		
Double demy ($22\frac{1}{2}" \times 35"$) . . .	2 000	$2\frac{1}{2}$	1 colour . . .	—	10
Double royal ($25" \times 40"$) . . .	1 800	3	4-12 colours . . .	—	25-50
Quad crown ($30" \times 40"$) . . .	1 800	$4\frac{1}{2}$	Calenders, mercerisers . . .	—	10-40
Quad royal ($40" \times 50"$) . . .	1 800	5	Starchers . . .	—	5-15
			Driers . . .	—	8-12

Table 163 includes useful data concerning miscellaneous machinery used in connection with printing work.

TABLE 163.—*Power Required to Drive Miscellaneous Machines in Printing Works.*

	H.P.		H.P.
Trimmers . . .		Platen machines . . .	$\frac{1}{2}$ -7
Folders . . .		Wire stitchers and binders . . .	$\frac{1}{2}$ -6
Round cornering . . .		Wharfedale cutters . . .	3
Punching, eyeletting . . .		Baling machines . . .	2
Bronzing, dusting . . .		Conveyors . . .	5
Envelope and label punching . . .		Linotype machines . . .	$\frac{1}{2}$
Cropper platen . . .		Ink mills (12×8 ins. to 24×12 ins.) . . .	3-5

778. Iron and Steel Works.—The iron and steel industry is the most important single consumer of electricity; *e.g.* it is estimated that it consumes about 20 % of the total kWh used by all the industries of the U.S.A. Electric driving is standard in modern iron and steel works, and where blast furnace gas is available it is applied to the generation of electrical energy, either being burnt below boilers serving steam turbines or used in gas engines driving flywheel-type alternators* (§§ 167, 181, Vol. 1). Even where full use is made of waste heat and fuel gas from blast furnaces and other furnaces, however, steel works purchase much energy from supply stations or, alternatively, maintain a large fuel-burning power plant. According to an estimate by G. Fox,† typical values for the energy consumption in iron and steel manufacture are :—

Coke ovens	3 kWh per ton of ingots
Blast furnaces	52 " " "
Steel works	5 " " "
Rolling	200 " " "
Auxiliaries	40 " " "
	<u>300</u> " " "

On the average, about 140 000 cu. ft. of blast furnace gas is produced per ton of pig iron made, and if one-third of this gas be used in gas engines requiring, say, 120 cu. ft. per B.H.P.-hr. (*see* Table 15, § 167, Vol. 1), or 170 cu. ft. per kWh, the electrical output available is about 275 kWh per ton of pig iron manufactured.

Electric driving is applied throughout iron and steel works from the blowers and skip hoists of the blast furnaces to the cranes and rolling mills, and their auxiliaries. The equipment includes main drives for the roughing, intermediate and finishing mills; auxiliary drives for the live rolls, lifting gear for the roll tables in 3-high mills, roll screws, etc.; cranes and hoists to lift and carry the steel at various stages in the sequence of heating, rolling and trimming operations; and other auxiliaries such as saws, shears, air compressors, and so on. The driving of rolling

* For particulars of a modern iron and steel works, including blast furnaces, power plant, steel-making equipment and rolling mills, *see* 'New Plant of the Appleby Iron Co., Ltd.,' by A. Croke and T. Thomson, *Iron and Steel Inst.*, May 3, 1928, and *Engineering*, May 3 and 11, 1928.

† *Power*, Nov. 29, 1927.

mills is probably the most severe service to which electric motors are applied, but the motors and control gear now built for the purpose have proved extraordinarily reliable in operation, and have increased the tonnage output whilst reducing the cost of finished steel and other rolled metals. At the same time, the working conditions in rolling mills have been greatly improved. There is a great saving of both skilled and unskilled labour, and the automatic control gear of an electrically driven mill attains an accuracy and speed which could not be approached by manual control. The radiation losses from steam boilers, pipes and engines are eliminated, and the consumption of an electric motor when running light is only 3 to 5 % of the full-load power, compared with 15 to 20 % in the case of a steam engine.

Owing to the serious consequences of even a temporary interruption in electricity supply, the main circuits of the steel works should be arranged on the ring principle with supply available at all vital points from two directions, preferably from substations fed through independent feeders. Where private power plant operates in parallel with public supply, the latter normally taking the base load and the private plant dealing with the peaks, a greater measure of security is obtained for operation, and reduced power can be continued with either of these independent sources of supply should the other fail.

Control gear for the mill motors, live roller motors (ingoing and outgoing), skids and screw-down gear, together with the requisite electrical instruments, are generally arranged on a platform or bridge spanning the mill approach side.

The power required to roll metals depends on the physical properties of the latter at the temperature of rolling, and on the extent to which the cross-sectional area is reduced, or, alternatively, the ratio in which the metal is elongated.* As the metal cools, the power absorbed for a given displacement of material increases rapidly; and tough materials such as manganese steel naturally absorb much higher power than mild steel or brass. Power-requirement data relating to particular mills will be found in descriptions of the latter in technical journals, proceedings of societies, and similar publications; and various authorities have

* For example, the power absorbed for a given reduction in area is approximately doubled if the steel cools from 2 200° F. to 1 900° F.

arrived at empirical rules enabling the power and energy consumption of rolling mills to be predicted with considerable accuracy.*

The output of a blooming mill depends upon the 'time of pass,' which varies inversely with the mean speed. The steel has to be gripped and discharged at low speed, hence, for maximum output, quick acceleration and quick retardation are required; both are obtainable with electric driving, which permits enormous peak-H.P. to be developed during acceleration by means of flywheel-storage sets. High torque is required, at the rolls, say 2 500 000 lb.-ft. when rolling heavy ingots to blanks for roughing, and 500 000-750 000 lb.-ft. for roughing slabs or reducing billets to squares. Rapid reversal is important in reversing mills, and up to 2 000 switching operations per hr. may be required, involving automatic acceleration for best results.

Wide speed control is generally necessary to cover the different requirements of various products in finishing trains. A separate motor for each housing gives full control of the rolling speed in the successive stages. Compound D.C. motors are generally employed, but induction motors with slip-regulating auxiliaries are also used.

In *merchant mills*, which are called upon to produce sections of widely varying section, the motor speed must be capable of regulation to suit different requirements, and the speed set for a particular run must be closely maintained notwithstanding variations in load due to cooling of the metal. A certain 12-in. mill of this type is driven by a 3 000 H.P. induction motor with a modification of Scherbius' speed control.

In *continuous or tandem mills*, steel passes through a number of 'stands' of rolls, one after the other, being converted from bloom to finished product by from 6 to 12 successive reductions without intermediate reheating. This method is obviously advantageous in the mass production of standard sections. The product of the emerging area of steel by the speed of delivery must be the same for all stands, otherwise the metal will be stretched or looped between stands. The motor speeds must be closely regulable and nearly independent of variations in load as caused, for example, by changes in temperature of the steel. The roughing and intermediate rolls may be belt and gear driven from an induction motor; individual driving by D.C. motors is generally preferred for the

* See, for instance, W. Sykes, *Amer. I.E.E. Trans.*, Vol. 31, II., p. 2051.

finishing stands, but induction motors with auxiliary commutator motors for speed control can be used.

A number of different solutions are possible when choosing the type and arrangement of equipment for the electric driving of rolling mills and their auxiliaries. The following notes* are instructive:—

The hand-to-mouth practice of buying steel requires that the mills be equipped to deliver a wide range of products within a single day, or sometimes within an hour; and to secure this necessary flexibility, they must be capable of operating over a considerable range in speed. For such drives, D.C. motors are available and also induction motors with speed-regulating equipment such as the Kraemer or Scherbius type. As a rule, where only one drive is involved the adjustable-speed induction motor should be given favourable consideration. On the other hand, if a single mill requires several drives, as is the case with the modern continuous-strip mill, D.C. motors will usually be found preferable with respect both to first cost and to flexibility of operation.

The trend in D.C. drive of continuous mills has been toward the provision of one or more motor-generator sets to supply power to each individual mill, thus making available the advantage of the generator-voltage-control system of starting the mill motors. In an installation of this character, the motor and generator fields should each be separately excited and a reversing potentiometer type of generator-field rheostat may be employed, permitting the excitation to be decreased to zero and built up in either direction all without opening the field circuit or operating a reversing switch. Thus the mill operator, by controlling this one rheostat, can start the mill forward or backward, adjust its speed to the needs of the moment, or stop it.

Synchronous motors are now applied to main-roll drives with unqualified success. The starting characteristics of this type of motor have been so improved that they are satisfactory for most types of mills. The primary reason for this application lies in the ability of the synchronous motor to improve the P.F. of the supply system. Compared with the induction motor, its efficiency is usually higher and its first cost is lower, particularly in large low-speed units. Thus for any constant-speed mill drive, the possibility of using a synchronous motor should not be overlooked.

The ventilation of main-drive motors and motor rooms has not been given sufficient attention. All the losses that occur in the motors and other apparatus are converted into heat; and while modern electric apparatus is highly efficient, these losses are by no means negligible. For example, the motors and motor-generators supplying power to a 48-in. hot-strip mill have full-load losses that generate heat at a rate equivalent to that obtained from the perfect combustion of 5 tons of coal per 24 hrs., and all this heat is liberated in the motor room. The motors are not fully loaded all the time but the losses do not decrease in direct proportion to the decreased load.

For auxiliary drives it has been customary to employ series motors, except where there was danger that the motor would reach an excessive speed during the lightly loaded portions of its operating cycle. One reason for the preference for the series motor is the greater torque it makes available for a given percentage overload in armature current. However, the series motor does not possess as great an advantage in this respect as is commonly supposed. For example, compare a series motor with a compound-wound motor which has sufficient shunt field to limit its no-load speed

* From a survey by H. A. Winne, *Gen. El. Rev.*, Vol. 31, p. 287.

to 150 % of its full-load speed. While both machines exert the same torque at 100 % armature current, at 150 % current the series motor develops but 10 % more torque than the compound-wound motor, and at 200 % current the torque of the series motor exceeds that of the compound motor by only 20 %.

The compound motor has several advantages which are now bringing it into increasing use for almost all kinds of auxiliary drives. The most important advantage is that this type of motor, unlike the series motor, will not run away at light loads, straining both itself and the mechanism to which it is connected.

Another tendency of to-day is to make the operation of auxiliaries as nearly automatic as possible. In those cases where a drive must be accurately stopped at a predetermined point in its cycle, it is advantageous to employ dynamic braking and the compound motor can be dynamically braked much more easily than can the series motor. The shunt field of the compound machine is always excited, whereas the series field of a series motor must be separately excited during the braking operation, and this requirement complicates the control and delays the action.

The benefits of automatic control are not confined to auxiliary drives. A great many motor-generator sets are being installed with pull-button automatic switching equipment. The starting of even a large synchronous motor-generator set is now accomplished by the operator's merely pulling a single control switch, after which the various devices function entirely automatically under the control of suitable relays until the set is on the line.

Extensive applications are also being made of automatic equipments on the 250-V D.C. circuits that supply steel-mill auxiliaries, to restore service as soon as the cause of the interruption has been removed.

Power Requirements.—The following data relate to a 28-in. reversing rolling mill at the East Hecla Works (Sheffield) of Hadfields Ltd.

Duty.—Rolling manganese steel rails, high carbon-steels, or 15-in. square ingots of ordinary steel to 2½-in. square billets in one heat. Average output, 15 tons per hr. (20 tons maximum). Cogging rolls, 28 ins. × 7 ft.; finishing rolls, 28 ins. × 6 ft. 6 ins.

Drive.—By double-armature D.C. shunt-wound motor supplied through an Ilgner flywheel motor-generator set built by the B.T.H. Co. The mill motor is capable of developing a constant torque of 125 ton-ft. at all speeds from 0 to 60 r.p.m. in either direction; and of developing a constant output of 3 200 H.P. at any speed from 60 to 120 r.p.m. in either direction. Overload capacity: 453 ton-ft. torque from 0 to 60 r.p.m. and 11 600 H.P. from 60 to 120 r.p.m. Maximum voltage 1 800 V applied to the two armatures in series. Commutating poles are provided and there are compensating windings in the main pole faces to neutralise the armature reaction.

Flywheel Motor-Generator.—A 1 800 H.P., 3 300 V, 50-cycle induction motor of 600 r.p.m. synchronous speed drives two 650-V D.C. shunt-wound generators rated at 1 800 / 4 750 kW at 500 / 600 r.p.m. and a cast-steel flywheel 11 ft. 6 ins. diameter, weighing 30 tons. Ward-Leonard control is used, a D.C. motor driving a mill-motor exciter and a generator exciter, and the field currents of the exciters being varied to alter the excitation of the mill-motor field and the voltage applied to its armature.

Control Gear.—Contactor-type starting and slip-regulating gear, actuated from the control platform on the mill. The principal instruments on the control platform

are an ammeter showing the input to the mill motor, and speed indicators for the mill motor and flywheel set. Reversal from full speed in one direction to full speed in the other is effected in 3 to 4 secs.

Auxiliary Motors.—Eleven 40 H.P., 500 r.p.m. (1-hr. rating, with 100 % overload capacity), D.C. series-wound motors with commutating poles are used to drive live rollers, skids, and screw-down gear. The 60-in. hot saw is driven by a 75 H.P. motor.

The following data, from various sources, indicates the general power requirements and equipment of typical modern mills:—

A 54-in. *reversing blooming mill* of the Bethlehem Steel Co., rolling ingots up to 18 tons or more is driven by a 750-V D.C. motor developing 7 000 H.P. continuously at 40 / 80 r.p.m., and up to 17 150 H.P. at 37½ r.p.m. Speed control is by generator voltage from 0 to 40 r.p.m. and by motor field from 40 to 80 r.p.m. A 5 000 H.P., 6 600 V, 375 r.p.m., wound-rotor induction motor with slip-regulation drives two 3 000 kW, 750-V D.C. generators in parallel. The motor-generator set has a 50-ton flywheel 15½ ft. in diameter, and gives up 35 000 H.P.-secs. of stored energy when the speed drops 10 %. A *roughing mill*, for rough-rolling wide flange girders from blanks produced by the above mill, is driven by a 750-V D.C. motor developing 7 000 H.P. continuously at 65 / 100 r.p.m., and 14 900 H.P. max. at 62½ r.p.m. The *finishing mill* has similar equipment.

A certain *slabbing mill*, 42-in. rolling 7½-ton, 47-in. × 20-in. × 72-in. ingots to slabs of from 4 to 6 in. × 36 to 42 in. section at the rate of 120 to 170 tons per hr. is driven by a 1 350-V shunt-wound, double-armature D.C. motor developing 6 000 H.P. at 48 r.p.m., and a peak output of 15 300 H.P. at 48 / 100 r.p.m. in either direction. A similar motor equipment also drives a 40-in. *plate mill* rolling 50 tons per hr. of ¾-in. plates from 8-in. slabs. A *tandem plate mill* of the Lukens Steel Co., rolling plates from 0·1 to ½-in. thick in widths up to 72 in. and length up to 35 ft., has a 2-high 34-in. reversing roughing stand driven by a 1 200 H.P., 380 V, 25 / 50 r.p.m. D.C. motor, and a 4-high reversing finishing stand with 23-in. working rolls driven by a 2 500 H.P., 660 V, 53 / 80 r.p.m. D.C. motor. A 3 000 H.P., 2 200 V, 3-ph., 60-cycle induction motor with slip regulator drives three 1 050 kW, 380-V D.C. generators, one for the roughing mill and two (with armatures in series and fields in parallel) for the finishing mill. The set includes a 49 000 lb. flywheel. A reversing 32-in. *bar mill* of the Standard Seamless Tube Co., reducing 1½-in. square billets to square blanks for seamless tubes, is driven by a 550-V D.C. motor developing 2 150 H.P. at 43 / 86 r.p.m., supplied by two 1 000 kW, 720 r.p.m., 275-V D.C. generators in series, the latter being driven by a 3 000 H.P., 2 200-V synchronous motor; naturally, no flywheel is used in this set.

An 11-in. *continuous-running bar mill* of Hadfields Ltd., comprising one 3-high and four 2-high housings rolling 2½-in. billets to ½-in. to 1½-in. rounds or equivalent sections is geared to a D.C. compound motor developing 400 / 800 H.P. at 150 / 250 r.p.m.; a 10-ft., 17-ton flywheel is placed between the motor and reduction gear. A 14-in. mill of the same type, with six 2-high housings, rolling 5-in. billets to 1 in. to 3-in. rounds or equivalent sections, is direct coupled to a 500 / 1 000 H.P., 75 / 150 r.p.m., D.C. compound motor, with a 12-ft., 40-ton flywheel.

In certain 10-in. *strip mills* of the United Strip and Bar Mills Ltd., the roughing rolls are driven by an induction motor developing 1 500 / 1 150 / 805 H.P. at 325 / 250 / 175 r.p.m., with a flywheel storage set comprising a 310 kW, A.C. commutating machine and a 420 H.P., 750 r.p.m. induction motor. Speeds above or below synchronism are obtainable; also, P.F. correction, the control being

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a modification of the Scherbius system. The finishing rolls are driven by 2 500 / 2 030 / 1670 H.P., 224 / 200 / 260 r.p.m. induction motor with a storage .. consisting of a 375 kW A.C. commutating machine and a 510 H.P., 750 r.p.m. induction motor.

The roughing and intermediate stands of a 14-in. *tandem strip mill* are belt and gear driven from a 1 800 H.P., 214 r.p.m. induction motor, the finishing rolls being driven by D.C. adjustable-speed motors rated at 600 H.P., 150 / 250 r.p.m.; 800 H.P., 210 / 315 r.p.m.; and 800 H.P., 260 / 390 r.p.m.; total 4 000 H.P. The maximum speed of delivery from the final stand is 1 325 ft./min., and the products range from 13 (American) gauge strip, 4-in. wide to 14 gauge, 10-in. wide. A larger mill, producing strip up to 50-in. wide, is driven by wound-rotor induction motors on the first four stands and D.C. motors on the last seven stands; total 21 800 H.P.

In a certain case, reversing mill *tables* are driven by two 100 H.P., 480 r.p.m., 280-V D.C. series motors. *Screw-down motors* for adjusting the spacing of rolls may be D.C. compound-wound motors of 40 to 100 H.P. *Live rollers* in a certain case are driven by a 40 H.P. motor. A 60-in. *hot saw* requires a 75 H.P. motor.

779. Cement Mills ; Paint Works ; Collieries ; Dockyards ; Ship Auxiliaries ; Miscellaneous.—Table 164 shows typical data for machinery in cement works and paint works; also, ranges of power requirements in colliery equipment. (*See also* Chap. 32.)

TABLE 164.—*Power Required in Cement Mills, Paint-making and Collieries.*

	H.P.		H.P.
<i>Cement Works.</i>		<i>Collieries (see also Chap. 32).</i>	
Breaker mills—		Windings	50-2 000
5-6 tons per hour	12-15	Haulages	15-200
9-10 " " "	20-25	Locomotives	25-100
Tube mills—		Pumps	5-500
2 tons per hour	40-60	Air compressors	20-100
6 " " " "	120-130	Fans	20-500
Wash mills*	75	Coal cutters	15-30
Slurry tube mills*	250	Percussion drills—	
Slurry paddles*	20	Light	1-3
Ball tube mills*	250	Heavy	5-10
Grinders*	300	Creepers	10-30
		Screens	20-200
<i>Paint Works.</i>		Washers	20-100
Edge-runner mills, 5-7 ft.	5-10	Coke breaker, 30 tons/hr.	4-5
Roller mills	2-6		
Cone mills	2-4		
Mixers	1-2		
Putty crushers	5-8		
Centrifugal disintegrators	10-20		

* These figures relate to the machines in a particular cement works.

Though necessarily far from complete, the data in Table 165 give a good idea of electric power applications in dockyards and on ships. (*See also* Table 151 and Chap. 37.)

TABLE 165.—*Power Requirements in Dockyards and Ships.*

	H.P.		H.P.
Graving-dock pumps	100-400	Capstans, windlasses . . .	20-150
Draining pumps . . .	15-25	Hoists, boat . . .	20-50
Dock-gate capstans	25	„ ammunition and tur	
Air compressors	60-120	ret . . .	3-15
Cranes . . .	20-100	Winches, deck . . .	10-40
Punches	15-20	„ coal . . .	50-150
Power hammer (5 cwt.)	20	Pumps, fresh-water . . .	5-10
Plate rolls	20-80	„ sanitary, bilge, and	
Fitters' shop	30-50	fire . . .	30-70
Dockyard motor-generators	100	Turret turning . . .	25
	upwards	Gun elevating . . .	15
Forced draught blowers	35	Torpedo air compressor	90
Steering gear . . .	50-150	Lifts . . .	5-15
Wireless set . . .	20	Ventilation fans . . .	1-10
X-ray set . . .	5	Machine tools . . .	1-5
Searchlight motor-generators	10	Galley machines . . .	1-5
	upwards		

The following miscellaneous data, taken from actual examples, may be useful as a general guide, though the requirements in particular cases vary considerably :—

	H.P.
Concrete mixer, 10-20 yds./hr. . .	5-10
„ „ 50-100 „ . . .	30-50
Carpet beaters . . .	5-10
Organ blower, per 10 stops . . .	$\frac{3}{4}$ -1 $\frac{1}{4}$
Dental engines . . .	$\frac{1}{8}$ - $\frac{3}{4}$
Rotary hair-brush . . .	$\frac{1}{8}$

780. Characteristics of Industrial Loads.—Information concerning the number of operatives employed and the types of engines and aggregate horse-power used in factories in the United Kingdom is to be found in the Census of Production,* which deserves to be studied carefully. The Census of Manufacturers prepared by the U.S.A. is, in some ways, more useful to the power engineer partly because it includes a more extensive analysis of data and partly because it relates to a country in which the industrial application of

* Taken periodically by the Census Office of the Board of Trade and published by H.M. Stationery Office. The Preliminary Reports of the Fourth Census of Production (1931) are now (1932) appearing fortnightly in the *Board of Trade Journal*.

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power has been developed to a remarkable extent. The volume of American manufactured goods in 1925 was $2\frac{1}{2}$ times that of 1899, but the number of employed was only 1·8 times as great; the output per worker thus increased 50 %, a development which is directly associated with the fact that the power used increased from 2·1 installed H.P. per wage earner in 1899 to 4·3 H.P. in 1925.

An interesting fact emerging from the American statistics is that four industries—iron and steel (21 %), textiles (11·1 %), food (10·8 %), and lumber (9·7 %)—account for 52·6 % of the total installed primary power of the nation. Paper (8·6 %), chemicals (8·3 %), and machinery (7·6 %) account for another 24·5 % of the total; leaving only 22·9 % to be shared by all other industries. Table 166 shows the installed primary power per wage earner in 50 leading industries in the U.S.A. in 1925.

TABLE 166.—*Installed Primary Power per Wage Earner in the United States of America.*

Industries.	Installed H.P. per wage earner in 1925.	Industries.	Installed H.P. per wage earner in 1925.
Agricultural implements . . .	4·0	Foundries and machine shops . . .	3·6
Automobile, bodies, etc. . . .	2·8	Furniture	2·2
Bakery products	1·4	Gas, illuminating	9·1
Blast furnaces	47·3	Glass	3·9
Boots and shoes	0·7	Hardware	1·9
Boxes, paper	1·3	Knit goods	1·0
Boxes, wooden	3·7	Leather, tanning, etc.	4·2
Brass and copper products	5·8	Lumber and timber products . . .	4·8
Brick and clay products	5·0	Malt liquors	26·8
Butter, cheese and condensed milk	7·1	Millinery and lace goods	0·2
Canning, fruit and vegetables . .	2·2	Paper and wood-pulp	19·7
Cars, steam railroad	2·0	Petroleum refining	6·0
Chemicals	11·8	Planing mill products	5·4
Cigars and cigarettes	0·8	Printing, book and job	1·8
Clothing, men's	0·8	Printing, newspapers, etc. . . .	2·0
Clothing, women's	0·2	Rubber manufactures	5·1
Coffee, spices, etc.	3·9	Shipbuilding, steel	6·0
Confectionery	1·6	Shipbuilding, wooden	2·8
Copper smelting and refining . . .	21·0	Silk goods	1·6
Cotton manufacturers	5·0	Slaughtering and meat packing .	3·7
Cotton-seed oil and cake	14·8	Steam-railroad shops	2·1
Dyeing and finishing textiles . . .	8·6	Steel works and rolling mills . .	12·9
Electrical machinery, etc.	2·5	Structural iron work	4·4
Flour mills and grist mills	21·0	Sugar refining	6·1
Food products, miscellaneous . . .	6·9	Woollen and worsted goods . . .	3·5
		All industries, United States . . .	4·3

Table 167, based on data compiled by Rushmore and Lof,* shows the average load factors of various classes of consumers; see also § 576, Vol. 2.

TABLE 167.—*Average Load Factor of Various Classes of Consumers.*

	L.F. %.		L.F. %.
<i>Small and medium lighting consumers.</i>		<i>Larger power and lighting consumers.</i>	
Public buildings	17.6	Bakeries	12
Churches	12.4	Breweries	45
Clubs	9.6	Department stores	30
Flats	6.9	Furniture manufacturing . .	28
Public halls	6.9	Foundries	15
Hotels	24.4	Ice making	30
Business offices	9.2	Laundries	20
Professional offices	6.7	Machine shops	20
Residences	7.8	Newspapers	18
Restaurants	23.4	Packing houses	30
Schools	7.2	Railway stations	50
	3 to 19	Textile mills	20

781. I.E.E. Rules Relating to Motors and Machine Control Gear.—The I.E.E. Regulations for the Electrical Equipment of Buildings (ninth edition)† contain rules Nos. 117 to 121 substantially as follows:—

MOTORS.

117. *Types.*—(A) Motors may be of any of the types enumerated in B.S.S. No. 168, or of the immersible type, and all motors rated at more than 1 B.H.P. shall conform in all respects to that Specification.

(B) The frame of every motor shall be provided with a suitable terminal to which the earthing lead may be connected.

118. *Position of Motors.*—(A) Motors shall, wherever possible, be placed in well-ventilated spaces in which inflammable gases cannot accumulate. Where these conditions cannot be complied with, the motors shall be of the flame-proof or pipe-ventilated type with inlet and outlet connected to the outer air.

(B) Motors fixed in situations in which the surrounding air exceeds the limit of temperature permitted for the cooling air in the appropriate B.S.S. shall be of special construction, or alternatively of the pipe-ventilated, forced-draught or induced-draught type, connected by ventilating ducts to a source of cool air supply.

(C) Motors shall, as far as possible, be placed in positions in which they are not exposed to risk of mechanical injury or to damage from water, steam or oil. Motors necessarily exposed to such conditions shall have suitable types of enclosing frames selected from the standard 'types of enclosure' specified in B.S.S. No. 168.

* Reprinted by permission from *Hydro-Electric Power Stations*, by Rushmore and Lof, published by John Wiley & Sons, Inc.

† According to the date of issue of the tenth edition, alterations in the above regulations will be noted in the fifth edition of Vols. 1 or 2.

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(D) Pipe-ventilated, forced-draught and induced-draught motors shall be supplied with air as cool as possible, and the air intakes shall be guarded against the admission of dirt and / or moisture.

(E) No unprotected woodwork or other inflammable material shall be within a distance of 12 ins. (30 cm.) measured horizontally from, or within 4 ft. (120 cm.) measured vertically above, any motor, unless such motor be of the totally enclosed, flame-proof or pipe-ventilated type with inlet and outlet connected to the outer air. A metal plate or tray extending 12 ins. (30 cm.) beyond the base of the machine shall be placed under every open-type machine which is mounted on a floor consisting of wood or other inflammable material.

119. *Control of Motors.*—(A) Every motor shall be protected by efficient means suitably placed and so connected that the motor and all apparatus in connection therewith may be isolated from the supply; provided, however, that when one point of the system of generation or supply is connected to earth, it shall not be necessary to disconnect on that side of the system which is connected to earth.

(B) Every motor shall be provided with an efficient switch or switches for starting and stopping, so placed as to be easily operated by the person controlling the motor; and every motor having a rating exceeding $\frac{1}{2}$ H.P. shall in addition be provided with—

- (a) Means for automatically opening the circuit if the supply pressure falls sufficiently to cause the motor to stop;
- (b) In the case of direct-current motors a starter or switch for limiting the current taken when starting and accelerating;
- (c) In the case of alternating-current motors, such starter or switch for limiting the current taken, when starting and accelerating, to the value (if any) required by the supply undertaking.

(C) In every place in which a machine is being driven by a motor there shall be means at hand for either switching off the motor or stopping the machine if necessary to prevent danger.

NOTE.—Suitable motor starters are embodied in B.S.S. Nos. 82, 117, 140, 141, 147, 155, and 167.

RESISTANCES AND MACHINE CONTROL GEAR.

NOTE.—Regulations 120 and 121 do not apply to apparatus having a capacity less than 60 W.

120. *General Construction.*—(A) The general construction of all resistances and machine control gear shall conform in all respects to the appropriate B.S.S.

(B) All live parts shall be so guarded as to prevent accidental contact with them.

(C) The frame of every resistance and control gear shall be provided with a suitable terminal to which the earthing lead can be connected.

(D) Resistances shall be so proportioned and placed that they do not rise to such a temperature as to impair their durability, and they shall be so disposed within their cases that no accessible part of such cases shall rise to a temperature higher than 176° F. (80° C.).

(E) Internal connections shall not be soldered, and all such connections, unless self-supporting or rigidly fixed in position, shall be continuously insulated with non-ignitable material or beads.

(F) Suitable terminals shall be provided for the attachment of external leads, and shall be so situated that such leads enter the case below the resistances and are not exposed at any point to a high temperature.

121. *Position.**—(A) All resistances and control gear shall, as far as possible, be placed—

- (a) In positions in which they will not be exposed to risk of mechanical injury or to damage from water, steam, or oil;
- (b) In well-ventilated spaces in which inflammable or explosive dust or gas cannot accumulate under normal conditions.

Where necessarily exposed to such conditions, control gear shall in the case of (a) be completely enclosed, and in the case of (b) be flame-proof; and resistances shall in the case both of (a) and (b) be completely enclosed.

(B) All woodwork or other inflammable material which is within a distance of 24 ins. (60 cm.) measured vertically above, or 12 ins. (30 cm.) measured vertically below, or 6 ins. (15 cm.) measured in any other direction from, the frames or cases containing resistances shall be protected with non-ignitable material.

782. Bibliography.—(See explanatory notes, § 58, Vol. 1.)

OFFICIAL REGULATIONS.

See Chap. 41 in this volume.

STANDARDISATION REPORTS, ETC.

British Standard Specifications.

No. 46.—*Part 1*: Keys and Keyways and Coned Shaft Ends. *Part 2*: Splines and Serrations. *Part 3*: Solid and Split Taper Pins.

No. 292.—Ball Bearings and Parallel-Roller Bearings.

No. 351.—Friction Surface Rubber Transmission Belting.

No. 367.—Performance of Ceiling-Type Electric Fans.

No. 380.—Performance of Desk-Type Electric Fans.

No. 411.—Attachment of Circular Saws for Woodworking.

No. 424.—Vegetable Tanned Leather Belting.

See also §§ 712, 745.

BOOKS.

Electric Drive Practice, G. Fox (McGraw-Hill).

Electricity in Steelworks, W. McFarlane (Pitman).

Electrical Engineering Economics, D. J. Bolton (Chapman & Hall).

I.E.E. PAPERS.

The Variation of Efficiency with Size, and the Economic Choice of Electrical Machinery, D. J. Bolton, Vol. 64, p. 837.

The Electrical Driving of Rolling Mills, H. S. Carnegie, Vol. 69, p. 1279.

MISCELLANEOUS.

Articles describing new installations of electric driving in various industrial establishments appear continually in the technical periodicals of all countries.

See also §§ 712, 745.

* See note above, Regulation 120.

ELECTRIC HOISTING, CONVEYING, ETC.

783. Nature of Hoisting and Allied Services.—The lifting, hoisting, or conveying of passengers or materials is simply a special case of general traction, but whereas 'electric traction' is generally understood to cover transportation on rails or road by means of locomotives or self-propelled vehicles, the applications dealt with in the present chapter generally involve the use of some fixed 'winding engine' (other than for mining; Chap. 32) and haulage by a rope or chain, either with or without the use of a track. No definite line of demarcation can be drawn, however. A transporter crane involves both traction and hoisting; a 'funicular' railway, with haulage rope and counterbalancing, might logically be considered in the present chapter, whereas a rack railway is a case of 'traction.'

The different varieties of conveying involve more mechanical than electrical problems, but the application of electric drive is of great importance owing to its convenience, flexibility of control, and high efficiency. The haulage of a container of any kind up an incline is exactly comparable with the propulsion of a vehicle up a hill, the differences in the application of the tractive effort being only mechanical. In both cases the work done = (Weight, in lb. \times Vertical lift, in ft.) foot-lb., *plus* the work necessary to overcome track friction, windage, internal friction of mechanism, and the electrical losses. Where an unguided load is lifted vertically as by 'cranes,' there is no track friction, and where a load is lifted vertically in a defined path, as by 'lifts,' the track friction is negligible in comparison with that obtaining with rolling stock. There are, however, losses of energy in other directions, as, for example, in the bending of ropes and in the additional gears which are generally required to obtain the lower speeds employed. Losses in main driving gears, and internal losses in driving motors, occur both in traction and in haulage of all kinds.

784. Energy Consumption for Hoisting.—As a first basis for estimation, the energy required for hoisting is: (Load, in lb. \times Vertical lift, in ft.) ft.-lb.; and 2 653 200 ft.-lb. = 1 kWh. This is, of course, the theoretical and absolute minimum consumption of energy to which must be added the frictional and other losses, and, with certain restrictions, the energy required to lift the dead-weight of the container and the rope. The energy consumed in hoisting dead-weight may be more or less completely eliminated by using balance weights, or by operating two containers with the one rope, the one rising while the other falls.

To hoist W tons at s ft./min. requires, theoretically, $2\,240\,Ws/33\,000$ H.P. If the horse-power actually required is P , the overall efficiency of the plant is $2\,240\,Ws \times 100 / (33\,000\,P) = 6.8\,Ws/P$ %. This formula is equally applicable to continuous conveying, if W represents the *tons per minute* conveyed from the lower point to the higher, and s represents the *vertical* component of the movement. Where the conveyor is entirely horizontal in movement, then no lifting occurs, the power supplied is consumed only in overcoming frictional resistances and electrical losses, and can only be estimated from experience of similar installations already in use.

785. The Counterbalance Principle.—Where passengers are to be hoisted, or conveyed up inclines intermittently, some form of cage or car is an obvious necessity and the power utilised for lifting this against gravity would be a dead loss were a single cage or car to be employed, for it is not generally practicable to apply, on the downward journey, any form of regeneration by means of which the energy stored in the lifted vehicle can be converted into electrical energy and returned to the supply system. Where hoisting in a free vertical path is involved, as with cranes, the load is frequently supported by some arrangement of slings, or in a container, of negligible weight, and no serious loss of energy results from leaving these items entirely unbalanced.

In passenger lifting it is possible to eliminate a large proportion of the energy loss which would otherwise result from hoisting the container, by adopting some means of counterbalancing the dead-weight of the container. In some cases this may be combined with a downward journey, as in funicular railways, by attaching two cars to the haulage rope, one at each end, the rope passing round the drum of the winding engine located at the top of the

incline. The one car will then rise while the other descends, and the dead-weights of the two cars will cancel out in all circumstances; the weight of the rope is not counterbalanced unless a tail-rope is used, as is sometimes done in mine-shaft winding. Although, in many instances, the passenger loads will similarly balance each other more or less completely, the power and other requirements must be determined for the extreme case of the rising car being full and the descending car being empty.

For passenger lifts in buildings it is not usually convenient to connect two cages in this manner, as such lifts cannot normally be operated on any time-table, but must travel at irregular intervals according to requirements. An occasional exception to this rule may occur as, for example, in the lifts between the second and third floors of the Eiffel Tower, Paris; here two lift cages are operated simultaneously from a single winding engine, the one working between the lower stage and the mid-level, and the other between the mid-level and the upper stage, the passengers on either journey changing cages at the mid-level. In most passenger and goods lifts, the dead-weight of the cage is balanced by a special counterweight, and, since the load may vary from empty to full load, it is the usual practice to design the counterweight to balance the *average* total load, *i.e.* the counterweight is made equal to (Tare of cage + *Half* the maximum useful load). The maximum upward effort to be applied by the driving mechanism is then limited to one-half the useful load, apart from frictional and accelerating forces. In colliery winding installations with two cages or skips it is practicable always to raise one while lowering the other; this permits practically complete balancing of the dead-weights.

786. Cranes: General.—Cranes are made in a variety of designs, which vary from the simplest form of 'jib crane,' or even a plain 'hoist' at the end of a beam, to complex forms such as the 'transporter' crane. At the one end of the scale the load is lifted vertically, without movement in any other direction, and the design then becomes more complicated as additional movements are superposed upon the elementary movement of lifting. Although much of the work of cranes is to lift materials through considerable heights, there are many applications, particularly those of loading and unloading ships, railway and road vehicles, where great vertical movement is unnecessary. In these cases the superposed motions may be of greater importance, as in the case of the work-

shop overhead travelling crane, and the dockside travelling jib crane.

The overhead 'runway,' which is of such great utility in workshops and factories, is merely a combination of some form of simple hoisting device, attached to a simple carriage which can be hauled along the runway by hand or driven by electric power.

In all variations of the 'crane,' the additional motions generally involve mechanical rather than electrical considerations. The various movements, other than the fundamental one of hoisting, may be classified broadly into two types: (1) Those in which the whole structure moves along some defined path or track, as in transporter cranes; or where part of the structure moves along some other part, as in the overhead travelling crane; and (2) those where portions of the structure operate as mechanism, *e.g.* the various motions of the jib in the many forms of jib crane. The former call for no explanation, but the latter type introduce certain complications. Jib cranes of all varieties are frequently arranged so that the whole structure may be rotated about a vertical axis with the jib in any position, so that the area of activity may be a circle or part of a circle. This rotational movement is termed 'slewing.' The usefulness of a jib crane is greatly enhanced by pivoting the jib at its foot, and providing means for varying the angle of inclination of the jib. If provision is made for altering the inclination, and therefore the radius of the jib by some sort of mechanical adjustment (usually without load on the jib), the crane then being used for some time with that setting of the jib, the crane is a 'derricking' crane. If, however, the provision for varying the jib inclination is one of the regular working movements of the crane, and can be used with load on the hook, then the crane is a 'luffing' crane. By using the 'luffing' motion, the load may be moved inwards from the vertical axis, in a vertical plane, *e.g.* for loading and unloading purposes on docksides. The addition of the 'luffing' motion, however, introduces a possible loss of energy, towards the elimination of which considerable ingenuity has been directed.*

If the jib of a crane be raised nearer to the vertical, the winding drum being stationary, the load is lifted through a height nearly

* A useful treatment of this problem, together with notes on all the principal types of electric cranes, is to be found in 'Electric Cranes,' by C. H. Woodfield, *Jour. Junior Inst. Engineers*, Vol. 82, Pt. 2, p. 47.

equal to the rise of the end of the jib. As a consequence, besides the energy required to lift any unbalanced part of the jib and its attachments, overcome friction and inertia, energy must be supplied to lift the load through the rise produced by luffing. Apart from any operating inconvenience of this movement, the energy applied to lifting the load through this distance is a dead loss, unless it so happens that the load is required to be lifted. To obviate this loss of energy, and to avoid the inconvenience of change of height, jib cranes are generally built on the 'level-luffing' principle, *i.e.* arrangements are provided whereby the load moves in a *horizontal* path when the jib is luffed. This may be secured by any one of many different arrangements, the details of which involve mechanical rather than electrical problems. Their application, however, effects an appreciable saving in the consumption of electrical energy. The basic principle employed is that either by paying out rope or by depressing a pivoted section at the end of the jib, automatically in both instances, the height of the load is kept constant notwithstanding the rise of the whole of the jib or the main part of it, as required to clear obstacles when slewing, or to move the load horizontally.

787. Cranes: Energy Supply and Types of Motors.—Permanent connections to the supply mains (through the usual switchgear) should be made wherever possible. Sliding or rolling contacts may be necessary to allow the desired degree of relative movement between parts of the crane itself, or between the crane and its supports. In other cases flexible leads and trailing cables (§ 820) may meet the requirements. (*See note, p. 417.*)

In overhead travelling cranes it is usual to employ bare trolley wires of hard-drawn copper, the current being collected by trolley wheels or sliding contact pieces, both for the main movement along the workshop and for the movement of the crab along the crane girders. In such cases the bare conductors are normally out of reach of the crane-driving personnel and the workpeople; their use is therefore permissible, but precautions must be taken to guard against accidental contact. This method is not practicable where current must be supplied from ground level, as in the case of transporter cranes, travelling gantry cranes, and the like. In such cases the supply is usually effected by means of long trailing cables, suitably armoured, which can be plugged into convenient points at intervals along the track.

Direct current is generally to be preferred for driving cranes of all types, owing to the smooth speed control obtainable, the good starting torque of D.C. series and compound motors, and, sometimes, the possibility of arranging for automatic regeneration of energy when lowering the load. Where the main supply is A.C. it may be advantageous to install a Diesel-electric set to provide D.C. Such sets are compact, reliable and economical. One Diesel-driven generator delivering 65 kW at 250 V and running at 900 r.p.m. may supply energy to three 5-ton cranes and one 3-ton crane.

In general, crane motors must be capable of withstanding excessive vibration and shock; of dealing with rapid variations of load, including occasional heavy overloads; and of providing a high torque on starting. In a clean, dry situation, enclosed ventilated motors may be employed, but in outdoor positions, especially where dirty or dusty loads are to be handled, the totally-enclosed pattern is essential.

The service being intermittent, the 'time factor' of operation, *i.e.* the ratio of the time of working to the whole time, should be taken into account when choosing a rating for the driving motor.

A common specification for crane hoisting motors is that they shall deliver their full load for 30 mins. with a temperature rise not exceeding 90° F., 25 % overload for 5 mins., and twice the full load momentarily. This will generally suffice for duty the time factor of which is about 1/6. The starting torque should be not less than twice the normal full-load torque. The following notes * concerning the choice of motor speed and rating for crane service are instructive :—

Except in very special cases, the $\frac{1}{2}$ -hr. rating is ample for crane and winch motors.

The $\frac{1}{2}$ -hr. rating corresponds to working all day at full load, 1 min. on and 4 mins. off. The 1-hr. rating corresponds to working all day at full load, 1 min. on and 2 mins. off.

It is only very occasionally, in the case of ordinary 3-motor cranes, that full load is required, hence the $\frac{1}{2}$ -hr. rating is usually ample.

The advantages of using a 'slow speed' motor (*i.e.* a motor of slow speed at full load) are that the first cost of gearing and the running losses are reduced; also, high speeds can be obtained at light loads, the speed varying more with load than in a high-speed machine. Generally, the crane is working at much below its maximum capacity, hence the 'slow speed' motor is usually running at a moderately high speed and working with high average efficiency.

* Abridged from 'Electric Motors' (4th ed.), a brochure issued by Laurence Scott & Co. Ltd., Norwich.

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D.C. series and cumulatively compound motors (§§ 676, 677) are specially applicable to hoisting service owing to their high starting torque and an increasing speed as the load is reduced. When winding is light, *i.e.* lifting only the hook, the speed may be twice the full-load speed. D.C. series motors must not, however, be used where the load could, from any cause, become light enough to permit them to race. An automatic centrifugal brake on the hoisting motion prevents excessive speed when lowering. Sometimes compound wound D.C. motors are used in order to limit the light-load speed. Slip-ring induction motors are often used in hoisting and conveying service.

It is often advisable, in the case of gantry and travelling cranes of high lifting capacity, to provide one or more auxiliary hoists of lower capacity and greater speed.

788. Crane Speeds and Control of Cranes.—The speed at which the load is hoisted, slewed or travelled depends largely upon the type of crane and nature of service concerned. Jib cranes for harbour service in loading and unloading ships should operate at high speed in order that vessels may make a quick 'turn round.' Hook speeds recommended for such service are :—

Load, tons.	Hoisting, ft./min.	Luffing, ft./min.	Slewing, ft./min.	Travelling, ft./min.
1 to 2	300-250	120	600-500	150-100
5	200-175	100	500-450	100-75
10	200-150	80	400	75-50
50	50	50	300	—

Overhead cranes in workshop service must be operated at much lower speeds in the interests of safety, bearing in mind the smaller lift required. Typical data are :—

Load, tons.	Hoisting, ft./min.	Traversing, ft./min.	Travelling, ft./min.
1 to 2	25-20	75-60	300-200
3	20	75-60	300-150
7½	12	75-60	350-150

The higher speeds of travel relate to cranes with driver's cabs, the lower speeds to cranes controlled from the floor.

The H.P. required to drive any particular 'motion' increases with the speed at which the motion is operated. This consideration may determine the adoption of low speeds of hoisting and travel where the crane is used only intermittently. On the other hand, if it is desired to make full use of the crane, all the speeds should be as high as compatible with safe operation and reasonably economical mechanical and electrical design.

Reversing drum controllers are generally used on electric cranes. They are operated by handle, or by rope or chain from the floor, as the case may be. In small and medium-sized cranes and allied equipment the controllers may be connected in the motor circuits, but the use of contactor control panels is increasing and this type of gear is practically essential on all the heavier machines. The driver's master-control gear then consists only of press-buttons and miniature drum controllers. For maximum safety and performance the driver should be accommodated in a control cab, which moves with the load in the case of travelling cranes and from which a clear view of the load and its landing-place can always be obtained. Full provision should be made for adequate speed control, including creeping speeds where it is necessary to deposit loads very gently (*e.g.* moulds in foundries). Resistances used for speed control must be rated liberally. Automatic brakes must be provided to hold the load in the event of failure in current supply; and automatic trips are required to prevent over-hoisting, over-lowering and over-travel.

Series resistance is generally used to control the speed of D.C. series-wound hoisting motors, and resistance in the rotor circuit in the case of slip-ring induction motors. The hoisting speed may be about $1\frac{1}{4}$ times full-load speed when lifting half the maximum load; $1\frac{1}{2}$ times full-load speed with $\frac{1}{2}$ -load; and twice the full-load speed when lifting the empty hook. As the speed control effected by series resistance varies with the load (§§ 718, 725) additional steps may have to be provided on the controller where it is desired to lift light loads very gently. In the case of a D.C. series-wound motor, resistance in parallel with the armature, as well as in series with it, can be used to obtain relatively low speeds at low loads, with little variation of speed between $\frac{1}{2}$ -load and no-load. As a minimum, the number of speeds provided by the controller should be four in each direction for motors up to 5 H.P.; six for 20-40 H.P. motors; and eight to ten for larger machines.

In handling ship's cargo and in other services, where it is desired

to hoist light loads quickly, use may be made of the 'discriminator' mentioned in § 718 to reduce the field of the D.C. series-wound hoisting motor on light loads. As long as the field is constant the natural rise in speed of the series motor with decreasing current is insufficient to enable the speed of hoisting to be increased in proportion to the reduction in the weight lifted, but by aid of a diverter, weakening the motor field, this desideratum can be approached.

789. Types of Cranes and Typical Data.—The distinctions between various types of cranes are mechanical rather than electrical. According to circumstances there are many possible ways of *hoisting* a load to any desired height: *traversing* it to any point across the width, and *travelling* it to any point in the length of a prescribed space; and *slewing* it to change its aspect or orientation. Electric driving offers to the mechanical engineer the most convenient and generally the most economical means of operating and controlling these motions individually. From the electrical standpoint the only distinctions between the infinite number of mechanical combinations and variations lie in minor problems of energy supply and control, and in the necessity for allowing more or less power to drive the dead-weights of the crane parts and overcome more or less mechanical friction. It is impossible here to deal with all types and sizes of equipment, but the following notes and data will serve as a useful guide.

Jib Cranes.—In its simpler forms, with a fixed or rotating post, and a fixed or slewing and derricking jib, this type of crane is too familiar to need description. Its most important refinement is the level-luffing device (§ 786), and it should be remembered that the jib crane can be applied to almost any type of stationary or travelling mounting; also, it can often be added as a useful auxiliary to cranes of the travelling crab type. A single motor may drive all the motions of a jib crane through suitable clutches and gears, but the convenience and performance are increased by using a separate motor for each motion.

Wide requirements as regards flexibility of operation are imposed on cranes, as harbour cranes, which have to deal with all loads within their scope, at speeds and lifts which vary considerably with the nature of the goods handled and the situations from which they are to be taken and into which they are to be placed. Lifts up to 100 or 150 ft. may be required so that high average speed is desirable; nevertheless, it must be possible to deposit

loads gently and accurately. High acceleration and retardation are therefore required. Special arrangements have been devised to meet these requirements with minimum loss of energy in control and with more or less recovery of energy by regenerative braking. In one such system a D.C. variable-speed shunt-wound motor is used in conjunction with an auxiliary motor-generator, and the result obtained is that the main motor can be operated on any one of a number of load-speed characteristics ranging in type from that of a shunt motor to that of a series machine. The inherent advantages of the series characteristic are thus combined with ability to run slowly and economically at any load.

A certain *level-luffing jib crane* on a portal mounting lifts up to 2 tons at 60 ft. radius. *Supply*—440 V, D.C. *Hoisting*—50 H.P., 250 ft./min. *Luffing*—5 H.P., 120 ft./min. *Slewing*—5 H.P., 380 ft./min. *Travelling*—15 H.P., 100 ft./min. *Total* 75 H.P.

In another instance a level-luffing jib crane has motors as follows: *Hoisting*—60 H.P.; 3 tons at 46 ft. radius lifted 178 ft./min.; 6 tons at 23 ft. radius lifted 89 ft./min. *Luffing*—3½ H.P. *Slewing*—15 H.P.; 1 rev. of jib in 20 secs. *Total*—78½ H.P.

A jib crane suspended from the underside of a crab or carriage on the gantry of an overhead travelling crane is termed an *underhung jib crane*. The advantage of this arrangement is that by traversing the crab and slewing the jib loads can be picked up or deposited outside the stanchions carrying the gantry.

A jib crane mounted on an electric battery truck forms a self-contained, mobile unit which is extraordinarily useful in dealing with loads up to 1 or 2 tons at a radius of from 4 to 10 ft.; cranes of this type can be obtained for loads up to 5 tons but they are then necessarily heavy and costly in order to obtain sufficient stability. The light run-about type capable of lifting ½-ton at 8-10 ft. radius and 1 ton at 4-5 ft. radius is the most generally useful.

Overhead Travelling Cranes.—A girder or bridge structure spanning the workshop or other space served is mounted on wheels at each end. These wheels run on horizontal tracks of any desired length. A carriage or 'crab' carrying the hoisting gear and, in the larger sizes, a cab for the driver, runs on tracks on the crane girder. Provision is thus made for *hoisting* the load; *traversing* it, by means of the crab; and *travelling* it, by moving the crane as a whole. A single-motor drive is feasible, and sometimes used, the several motions being driven through belts, clutches, and square

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shafts; alternatively, a single motor may be used on the crab for hoisting, the crab being traversed and the crane travelled by manually operated chains and gearing. In general, however, it is preferable to operate each motion electrically and from a separate motor. The data in Table 168 are based on a number of actual installations of spans ranging from 30 to 60 ft. The span affects the total weight but not the motor H.P.

TABLE 168.—*Overhead Travelling Cranes.*

Load in tons.	Hoisting.		Traversing.		Travelling.		Total H.P. of Motors.	Approx. Weight of Crane, in tons (Depending on Span 30-60 ft.).
	Motor H.P.	Ft./min., fully Loaded.	Motor H.P.	Ft./min., fully Loaded.	Motor H.P.	Ft./min., fully Loaded.		
3	8	20-25	2	60-100	8	200-300	18	7-14
5	10	20	3	60-100	10	200-300	23	8-16
10	15	12-15	3-5	60-100	12	200-300	30-32	10-20
20	20	8-10	6	60-85	20	200-250	46	15-28
50	30	6	12	55-75	30	180-250	72	25-48
80	40	5	18	50-60	40	120-150	98	42-65

For convenience and economy, the larger cranes should be fitted with auxiliary hoists ranging from, say, 5 tons lifting capacity on a 20-ton crane to 15 tons on a 80-ton crane. This would add 2 or 3 tons to the total weight of the crane.

In some instances cranes and auxiliary hoists are fitted with hoisting motors of about twice the H.P. and lifting speeds shown in Table 168. In other cases change-speed gearing is fitted so that half or one-third of the maximum load can be lifted at twice or three times the full-load speed.

The 'hammer-head' crane may be regarded as an overhead travelling crane which 'travels' by rotation in a horizontal plane instead of along straight rails.

Hammer-Head (or Tower-Type) 150-ton Dock Crane.—The counterbalanced head of the crane rotates in a horizontal plane on top of a lattice tower, and carries a crab with hoisting gear. *Supply*—110 V, D.C. *Hoisting*—Two 17½ H.P. motors hoist 150 tons at 2½ ft./min.; 37 tons at 10 ft./min.; 18 tons at 20½ ft./min. *Crab Traversing*—One 26 H.P. motor; 26 ft./min. *Slewing*—One 26 H.P. motor; 1 rev. of crane head in 7·2 mins. *Total*—87 H.P.

Gantry and 'Goliath' Cranes.—These cranes consist of a portal-type structure running on rails for any desired distance

and provided with a hoisting-crab that moves to and fro on the girder or gantry for traversing the load. The motions are generally driven by separate motors. The following data relate to actual machines; obviously, the requirements may vary indefinitely.

Independent motors throughout. *Supply*—440 V, D.C. (i) 3-Ton Crane. *Hoisting*—10 H.P., 25 ft./min. *Traversing*—5 H.P., 90 ft./min. *Travelling*—15 H.P., 250 ft./min. *Total*—30 H.P. (ii) 3½-Ton Crane. *Hoisting*—65 H.P., 200 ft./min. *Traversing*—10 H.P., 200 ft./min. *Travelling*—10 H.P., 100 ft./min. *Total*—85 H.P.

75-ton wharf gantry crane, with 90-ft. boom or jib normally projecting horizontally, but capable of being lifted about its inner end. The jib has a 10-ton hoist at the outer end; and there are 50-ton and 25-ton crabs which can be used together to lift 75 tons. *Supply*—220 V, D.C. *Hoisting*—50-ton crab: 50 H.P., 10 ft./min. 25-ton crab: 50 H.P., 20 ft./min. 10-ton hoist: 25 H.P., 25 ft./min. *Crab Traversing*—50-ton crab: 25 H.P., 75 ft./min. 25-ton crab: 25 H.P., 150 ft./min. *Travelling*—100 H.P., 60 ft./min. loaded; 150 ft./min. light. *Elevating boom*—50 H.P. *Total*—325 H.P.

A floating gantry 450-ton crane mounted on two barges, one containing a 110 kW, 250 V steam-driven generator for power supply, has been used to lift 450-ton blocks of concrete in harbour construction (Algiers). The gantry carries a rotating tower or turret with two crabs. The motor H.P. and motion speeds are: *Hoisting*—Two 71 H.P.; 2.3 ft./min. lifting; 3.95 ft./min. lowering. *Crab-Traversing*—Two 28 H.P.; 13.2 ft./min. *Slewing*—Two 28 H.P.; 1 rev. of tower in 3 mins. *Hooks*—Four 1.65 H.P.; opened or closed in 25 secs. *Total*—261 H.P.

Transporter Cranes.—These are built in many different forms, all consisting essentially of a combination of a travelling gantry crane with an electric runway. A grab-bucket or other lifting device or container is hoisted by a motor on a crab or trolley which runs to and fro on the transporter bridge, the latter travelling on rails, overhead or on the ground. A cantilever or projecting boom is generally a distinctive feature of this machine; and provision may be made for the trolley to leave the bridge and go far afield on a runway. A rough estimate of the probable power requirements in any particular case may be based on the data given for overhead and gantry cranes and electric runways.

Grab Buckets.—These may be used with any type of crane to handle coal, earth, or other loose material. There are two distinct functions to be performed, *viz.* the closing (or opening) of the grab and the hoisting (or lowering) of the latter. In one common arrangement, the outer edge of each half of the grab is attached by tie-bars to a crosshead hung from the hoisting ropes, while the inner edge of each half is attached to a second crosshead hung from the grab-closing ropes. Raising or lowering the latter, *relatively*

to the hoisting ropes, closes or opens the grab by a toggle action. Each pair of ropes goes to a separate winch drum, so that the closing ropes can be operated independently of the hoisting ropes, to close or open the grab. Normally, however, both sets of ropes must be taken in or paid out at the same rate so that the bucket is raised or lowered without dropping its load. Both winches may be driven by a single motor, but for heavy service (say more than 3 tons total load) it is usually considered preferable to employ two motors, each of half the total H.P. required for hoisting, and each geared to one winch. Normally the controllers for the two motors are coupled mechanically by a device which ensures both being on the same notch, but the coupling can be interrupted to allow the closing winch to be operated independently for closing (or opening) the grab.

790. Electric Pulley Blocks and Runways.—The electric pulley (or lifting) block consists essentially of a high-speed motor (usually a D.C. series machine) geared down to a rope drum, and fitted with an automatic brake with electro-magnetic release or with a self-sustaining worm-gear reduction. The whole is assembled as a compact, totally-enclosed unit which can be attached to any suitable girder, or hung from the hook of an existing hand crane. If the unit is provided with trolley wheels it can be hauled by hand, or driven by its own power, along the flanges of 'runway' girders. The controller is built on to the pulley block and operated by pendant chains from the floor level. When selecting these machines it should be remembered that the maximum lift is the height of the suspension beam, etc., *minus* the overall height of the block and its sheaves and hook. Typical data are given in Table 169:—

TABLE 169.—*Approximate Speeds and H.P. of Electric Pulley Blocks.*

Lifting Capacity, Tons.	$\frac{1}{2}$.	1.	2.	3.	5.
Hoisting motor, H.P. . . .	1 $\frac{1}{2}$ -2	1 $\frac{1}{2}$ -3	3-4	4 $\frac{1}{2}$ -6	7-10
Hoisting speed, ft./min. . . .	20-23	10-20	10-13	10-13	10-13
Travelling motor, H.P. . . .	1	1 $\frac{1}{2}$	1 $\frac{1}{2}$	2	2 $\frac{1}{2}$
Travelling speed, ft./min. . . .	100	100	100	100	80
Max. lift, ft.	20-40	20-25	20-25	20-25	15-25

An electric runway consists of an overhead running track, often the lower flange of an I-beam; a self-propelling electric pulley

block or hoisting winch, with a driver's cab attached in the larger installations; and contact wires for the supply of electrical energy to the travelling hoist. (*See note, p. 417.*)

791. Electric Winches and Capstans.—These machines comprise an electric motor driving a rope drum or capstan through suitable reduction gearing. The capstan, being a vertical-spindle machine, may be driven through worm gearing by a horizontal-shaft motor placed in a watertight chamber beneath the capstan; or a vertical-shaft motor may be located more or less completely inside the capstan head. Automatic starting and safety gear is commonly provided, the operator having only to close a master switch to start the motor. For easy control of the haulage operations it is convenient to start the motor on light load and to engage the motor with the rope drum, as required, by means of a clutch pedal. The requirements of such a case are well met by a D.C. compound-wound or a squirrel-cage A.C. motor.

Theoretically, about $6\frac{3}{4}$ H.P. is required per ton of rope pull per 100 ft. / min. of rope speed; actually, the allowance should be from 10 to 13 H.P. per ton pull per 100 ft. / min., relatively higher power generally being needed in small than in large machines. The data in Table 170 may serve as a basis for general estimates.

TABLE 170.—*Electric Winches and Capstans.*

Rope Pull, Tons.	Rope Speed, Ft./Min.	Motor, H.P.
$\frac{1}{4}$	100	3
	150	5
	250	$7\frac{1}{2}$
$\frac{1}{2}$	100	6
	150	10
	250	15
1	100	10-12
	150	15-18
2	100	20-25
5	50	25-30
10	80	30-35

The Austin constant-current system, described more fully in § 678, offers special advantages in the driving of hoisting winches, haulage capstans, and, in fact, wherever a wide range of speed control at full load is desired. From the nature of the case a

motor in a constant-current circuit cannot be damaged by overload. When the overload becomes high enough, the motor will be stopped but the current will still remain at the constant value of the system, instead of rising to a destructive extent as it would in a constant-voltage system under short-circuit conditions. Also, the stalled motor will continue to exert more than the full-load torque and will therefore 'hold' its load. Finally, as the motors are regenerative, loads which are being lowered help to lift others which are being hoisted at the same time.

The I^2R losses in the circuit cables of a constant-current system are constant and continual (§ 317, Vol. 1). The system is therefore wasteful, so far as the distribution of heavy currents at medium voltages is concerned, unless the loads are close together, the use of very heavy conductors to reduce the I^2R loss in long circuits being economically impracticable. Probably the most favourable opportunity for the use of this system is on shipboard, where a large number of motors are necessarily installed in a relatively small space, and the simplicity of the series circuit, together with the absence of circuit breakers and fuses, is specially appreciated.

792. Electric Lifts: General.—Electric driving is generally the most convenient and economical method of operation for lifts, with the possible exception of those handling heavy loads over short distances, for which the hydraulic system may be preferable. Usually, the advantages of electric over hydraulic driving lie in the readier provision of suitable safety devices; the wider range of manual and automatic control methods that may be incorporated; the less space occupied in the building; lower initial cost; and smaller expenses for power consumption and maintenance.

Lifts may be divided into two main classes, *viz.* passenger lifts and goods lifts; and passenger lifts may again be divided into express types and slow-speed types. In all cases, the control gear and safety devices are of great importance, and it is desirable to seek advice from makers when planning any scheme of lifts, in view of the necessity for conforming to building regulations, and securing the most economical, reliable and suitable arrangements.

The general arrangement of an electric lift installation is for the car to be suspended from an arrangement of steel wire ropes, the car being guided laterally by suitable runners for the whole depth of the shaft or well. The hoisting rope passes to a motor driven winding engine and the car plus a proportion of the load is usually

counterbalanced to reduce the energy consumption. Counterbalancing is sometimes dispensed with in goods lifts of small travel, where the energy consumption in respect of the top speed travelling is small compared with that required for acceleration.

With the larger installations, it is a common practice to use two counterweights, *viz.* a drive counterweight and a car counterweight. The ropes connecting the car to the drive counterweight pass over the winding pulley, while those from the car to the car counterweight pass over idle pulleys. The purpose of the 'car counterweight' is to reduce the load on the driving pulley shaft and axles.

Multiple cables are generally employed for both car and counterweight, providing ample safety and reducing the bending stresses on the ropes. It is usual to counterbalance the car and the average load very closely, so that the energy consumption is restricted as nearly as possible to overcoming frictional resistances, and starting and accelerating the load. The more usual methods of control demand some electrical connection between the lift car and the fixed wires in the lift well. This is provided by flexible cables suspended from below the car floor and anchored to a junction box at the centre of the lift well depth.

The simplest and lightest arrangement is to place the winding engine at the head of the shaft, and carry the cage and counterweight from a single 'fall' of rope passing over the driving pulley in the case of traction sheave drive, or to carry the car and counterweight each from a single fall of rope attached to a winding drum. This arrangement involves least frictional losses, shortest length of ropes, and minimum load on the building. The speed of the car is then always equal to the circumferential speed of the driving pulley or drum, and it is arranged, wherever possible, that the sheave diameter equals the distance between the car and counterweight ropes, thus avoiding guide pulleys with their attendant losses, cost and maintenance.

Circumstances may sometimes demand that the winding engine be placed at the foot of the shaft, the rope or ropes then passing upwards, and over a head pulley before attachment to the car or counterbalance; this doubles the load on the building and results in additional frictional losses. Also, the rope is subjected to reversed bending which imposes additional stresses upon it. The usual practice of lift manufacturers is to adopt the overhead drive where circumstances permit.

The invariable practice is to run each lift in its own shaft or well. A suggestion has been made in the U.S.A., however (where the 'zoning' regulations diminish the floor area on the upper floors of tall buildings), that two lifts be run in a single shaft, both operating in the same direction with a pre-determined headway under automatic control. Such an arrangement would provide a greater lift capacity for the upper floors of such buildings.

793. Methods of Driving Lifts.—The actual drive to the suspension ropes may be either by winding drum or by traction sheave, and the latter method includes two sub-divisions, full wrap traction and wedge drive traction (also termed half-wrap traction, or V-groove drive).

The winding-drum system, formerly very common, has been largely superseded for lift work by the others, except for short travels and heavy loads. The ends of the hoisting cables are attached to the car and the drum respectively, and those of the drive counterweight to the drum and the balance weight. The drum is machined with two sets of helical grooves, of shallow circular section, so that the one set of cables is paid out as the other is wound up. Where an additional car counterweight is employed, the cables connecting this with the drum pass over idle head pulleys distinct from the winding engine. A positive drive is obtained, which, however, is not an advantage should the car be brought against the stops owing to failure of the limit-travel switches, as severe forces may then be applied to the mechanism. Provided that the drum is of sufficient diameter, the drum drive prolongs the life of the ropes by eliminating slip. The greatest disadvantages are that the drum cannot be made standard, since it must accommodate the whole length of rope to be wound up, and that with long travels the length and weight of the drum become excessive.

The two traction systems drive by friction; the hoisting ropes are attached at the ends to the car and the drive counterweight, and pass over or round the driving sheave, which has separate parallel grooves. The design of the sheave is independent of the length of travel, permitting of greater standardisation, and the space and dimensions of the driving shaft are not affected by the total travel.

In the full-wrap traction system, frequently employed in America, the driving sheave is grooved with shallow circular grooves on which the cables bed. A secondary pulley, or idle

pulley associated with the driving sheave, must be used to obtain the necessary 'coil friction' effect equivalent to a complete turn of the ropes round the driving sheave. These secondary pulleys are slightly smaller than the driving sheave and are placed close thereto. The cables from the car pass over the traction sheave, then over the secondary sheave, back over the traction sheave, and thence to the counterweight. The shallow bedding grooves employed maintain the tractive effort at a constant value, not being so subject to wear as are the V-grooves of the wedged drive system described below. The system has the advantage that the angle of lap round the traction sheave is the same for all widths of car. With the winding gear at the head of the shaft, and one-to-one roping, the ropes are always subjected to bending in one direction, but reversed bending occurs when two-to-one cabling is adopted, which circumstances sometimes demand.

The wedge drive or V-groove traction system is the simplest of all and is the method generally favoured in this country. One-to-one cabling is commonly employed and the shortest possible length of cable is then required. The driving sheave is turned with the parallel V-grooves in which the hoisting ropes wedge themselves. A greater frictional effect is thereby obtained, so that a half lap round the sheave is ample. The hoisting cables are then attached at their ends to the car and the drive counterweight, and pass over the traction sheave. For exceptionally heavy loads, the cable is reeved with a two-to-one ratio. With a car so wide that it is impracticable to use a sheave of sufficient diameter to give the half lap, a diverting idle pulley must be used to keep the counterweight clear of the car, and in such cases it may be desirable to revert to the full-wrap drive. Although the V-grooves are subject to wear by the rope, and there is some crushing effect on the ropes, experience has shown that these effects are of no great importance.

Two methods are in common use for rotating the driving sheave or drum—the geared system and the direct drive. In the geared system a high-speed motor is used, driving the final shaft through some form of gearing. The direct drive requires a low-speed (and therefore larger) motor, the driving sheave or drum being keyed directly to the armature shaft.

The geared system is favoured in this country, and now usually employs worm-reduction gearing. When the number of threads

on the worm is small, and the efficiency does not then exceed 50 %, the worm drive possesses the great advantage of being self-locking, so that there is no possibility of the load driving the motor. Worms with less than two threads are seldom employed. The worm is preferably placed below the worm wheel, so that the meshing gears run in an oil bath, but winding engines with the worm at the top are not uncommon in smaller installations, as this arrangement enables the complete winding engine to be made rather smaller and lighter. The worm drive offers the smoothest operation when carefully made and is probably the commonest type in use. The end thrust is, however, considerable, and for heavy loads in continuous service the tandem worm drive has been employed, in which worms of opposite hands on the same shaft drive two worm wheels so located that their teeth mesh. The three points of contact minimise the gear pressure and end thrust is eliminated.

Alternative gear systems adopted are spur gear (either internal or external) and double helical gearing, which require accurate manufacture and mounting to ensure quiet and smooth operation.

Horizontal motors are generally employed, but where floor space is very restricted it may be preferable to use a vertical-shaft motor. The position of the worm wheel and rope-driving sheave remains unaltered, but the motor and worm are swung through 90° in a vertical plane, and the brake is fitted to an extension of the upper end of the motor shaft. In a particular case * a vertical shaft motor complete with worm gearing and traction sheave, for capacities up to 1 000 lb. at 100 ft. per min., measures $24\frac{1}{2} \times 19\frac{1}{2}$ ins. \times 36 ins. high.

The direct-drive or gearless system has been extensively employed in the U.S.A., and provides a very smooth and quiet operating machine with high efficiency at full speed on long travels. It is generally employed with the full-wrap traction drive and requires a very low speed D.C. motor, although two-to-one roping enables a faster, and therefore lighter, motor to be used. Since the diameter of the driving sheave must usually exceed about 40 times the rope diameter, in order to limit bending stresses on the cables, the system is restricted to the higher lifting speeds; with one-to-one cabling, speeds generally lie between 350 and 700 ft. per min., but can be

* See *Power*, Vol. 67, p. 923.

reduced to between 400 and 500 ft. per min. with two-to-one cabling, the motor speed being of the order of 65 r.p.m.

In an actual American installation of this type the motor speed of 63.6 r.p.m. with a 36-in. sheave corresponds to a running speed of 600 ft. per min. The saving in first cost of the gearing is largely offset by the additional costs of the low-speed motor and the absence of the self-sustaining feature of the worm gear.

794. Running Speed of Lifts.—The choice of the running speed of a lift depends upon a number of factors, including: the total travel; the type of service, *i.e.* the number of stops in the travel; the type of control; the scope of the safety devices fitted; and, over-riding all, the regulations of local authorities and insurance companies.

Passenger lifts generally operate at higher speeds than goods lifts, as the time element is of greater importance with a human cargo, except in certain manufacturing operations where the rapid delivery of material may be of prime importance in maintaining continuous production.

In all cases a certain distance is required for the running speed to be reached from rest, and for a moving lift to be stopped. These distances are obviously travelled at varying speeds below the running speed, and can only be reduced by increasing the acceleration. A high acceleration imposes high forces on the whole of the mechanism, requires a correspondingly powerful drive, and, in the case of a passenger lift, is apt to impose more or less discomfort on the passengers. An acceleration of 5 ft. per sec.² is generally considered to be the maximum to which passengers may be safely subjected; and with a running speed of 600 ft. per min. this requires a distance of 10 ft. for starting or stopping. On the other hand, Marryat * has found it possible to accelerate a lift to 300 ft. per min. in 2 ft. (acceleration = $6\frac{1}{2}$ ft. per sec.²), or to 600 ft. per min. in less than 4 ft. (acceleration = $12\frac{1}{2}$ ft. per sec.²) without discomfort to passengers, provided that the acceleration be very smooth. With a given acceleration, a high running speed cannot be reached unless there is a sufficient distance from start to stop. Furthermore, unless there is an appreciable distance over which the running speed can be maintained, the driving motor will operate under uneconomical conditions for the majority of its

* *Jour. I.E.E.*, Vol. 62, p. 330.

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working time. A suitable running speed is, therefore, largely a function of the travel and the distance between stops.

A higher speed is generally permitted when a passenger lift is under the direct control of a regular operator than where automatic (push-button) control is employed; thus the automatic lift is inherently a time and power waster, since the passengers run the car with no regard for the demand from various floors. Where exact levelling of car with floor is desired, a further restriction is imposed by the careful control of deceleration required on stopping. The addition of safety devices, always desirable with passenger lifts, reduces still further the time available for top-speed operation by reason of the time required for shutting doors, landing gates and the like, and for the operation of the various relays and other control gear, increasing the loading and unloading times.

The speeds at which passenger lifts are generally operated in Great Britain are approximately as follows:—

	Ft. per Min.
Lifts in offices and flats with car switch control (by attendant)	200-350
Lifts in offices and flats with push-button control	100-200
Large lifts, <i>e.g.</i> in underground railways	about 180

Data relating to actual installations will be found in Table 171, § 800.

Much higher speeds are commonly employed in the United States, where greater scope is offered by the presence of 'skyscraper' buildings. Typical speeds in American installations are:—

	Ft. per Min.
Travel up to 100 ft.	350-400
Travel up to 150 ft.	400-550
'Express' services, stopping at only a few selected floors in the highest buildings	550-600
'Express' services in exceptional cases, where regulations permit	700-800

It is unlikely that speeds in Great Britain will exceed 600 ft. per min. for many years to come, as there are few buildings with ten or more stories.

For goods lifts, the ranges of speed are less well defined and vary greatly among different installations, according to the load and service. With loads from $\frac{1}{2}$ to 5 tons, speeds commonly range from 250 to 25 ft. per min. Representative figures from actual installations will be found in Table 171, § 800.

795. I.E.E. Rules for Electric Lifts.—Regulation 122 in the ninth edition of the I.E.E. Regulations for the Electrical Equip-

ment of Buildings (Wiring Rules) imposes the following requirements on every electric lift or hoist (*see* footnote †, p. 357):—

(a) It shall be operated from a circuit which is independent of the lighting installation.

(b) The multi-core trailing cable shall comprise the requisite number of conductors to keep the motor wiring and the control and safety devices entirely separate.

(c) The control and motor leads shall be in separate conduits.

(d) Except in special cases, such as chemical works or cold stores, all cables for any purpose in the lift or hoist shaft, except trailing cables, shall be armoured (Regulation 87, Class R) or shall be enclosed in metal conduits complying with Regulation 87 (Class T1 or Class T2).

796. Motors for Lift Driving.—The conditions under which lift motors must operate vary over a wide range. The load may vary from full positive load (or even from 20 % overload) to a negative load or ‘overhauling,’ and good speed regulation at all loads is an important feature. The static friction after the machinery has been standing idle is usually large, and this, combined with the need for quick acceleration, demands a starting torque up to some $2\frac{1}{2}$ times the full-load running torque. It is also important that the rotating parts shall have a relatively small inertia to facilitate rapid starts and stops, although, on the other hand, an appreciable flywheel effect assists in preventing sudden speed variations. To reduce the inertia effects the armature should be small, light, and run at a moderate speed. The speed is usually below 1 000 r.p.m., but higher speeds are sometimes used, especially in small installations with low speed of travel. Quiet running is a very important consideration.

A lift motor must obviously be of a type which can be started easily and quickly. High starting torque is essential for rapid acceleration, but the speed of the motor must be incapable of exceeding a predetermined maximum, corresponding to the desired maximum speed of travel, however light the load. According to requirements, the motor may run always at the same speed (subject to variations caused by its inherent speed regulation) after acceleration is completed and until deceleration commences; or provision may be made for running it at reduced speed by means of an appropriate controller. These requirements are met

by the D.C. compound-wound motor (§ 677) and the A.C. slip-ring induction motor (§ 683), which are the most commonly employed types (see Table 171, § 800); also, by induction-repulsion and variable-speed A.C. commutator motors. For further information on motors, motor control and driving, see Chaps. 28 to 30.

Shunt-wound D.C. motors are used in some small installations, but the cumulative-compound motor is to be preferred, owing to the improved starting torque resulting from the series winding. If desired, the latter may be cut out when the motor is up to speed, so that the machine then operates with the constant-speed characteristic of a plain shunt motor.

Speed control of an induction motor is generally by rotor resistance and then involves I^2R losses (§ 725). In the case of D.C. drive, speed control may be by shunt field variation or by variable voltage control (§ 716). The auxiliary motor-generator required for variable voltage control may also serve the purpose of enabling a D.C. lift motor to be employed where the main supply is A.C. Rheostatic losses are eliminated by this method of control, and the smooth acceleration obtained is specially valuable where high-speed lifts are concerned.

In a certain American 18-story garage building there are three motor-car lifts. Each lift car weighs 26 000 lb., has a useful load of 8 000 lb., and is driven by a 65 H.P. gearless motor running at 65 r.p.m. Three 60 H.P. motor-generator sets provide variable voltage control. The speed of travel of the lifts is 300 ft. per min., and the cars can be stopped in 15 ft., corresponding to a deceleration of 0.833 ft. per sec.².

Three-phase motors are generally preferred where A.C. supply is used without conversion, but many single-phase installations are in satisfactory operation (see Table 171, § 800). Particulars of a single-phase, shunt-type, two-speed motor are given in § 734. This machine operates a 6-floor lift in a busy office; the supply is 440 V, 1-phase, 40 cycles; and the capacity is 15 cwt. at 200 and 100 ft. per min., the lower speed being used when retarding, to facilitate smooth landing.

A wide change of speed (3:1 or even 6:1) for landing purposes is sometimes obtained by the use of pole-changing motors (§ 725).

797. Control of Lifts.—The nature of the problem demands that lifts shall be fitted with some form of remote control, and the fact that the operation is seldom in charge of those having any electrical knowledge further requires that a certain amount

of automatic working shall be incorporated in even the simplest control systems.

Lift control gear must be designed and constructed to permit of frequent and severe operation. An inexperienced or careless operator will employ 'inching' to a large extent where automatic arrangements for exact landing are not provided, thereby throwing unnecessary work on the control gear. Furthermore, many lift installations are not under regular expert supervision.

The necessary power switches, with their operating relays, fuses and other equipment are mounted on a panel near the motor, and connected by suitable cables to the associated apparatus, such as resistances, also located nearby.

The main functions of the controller are: (1) To start the motor and accelerate it to full speed in either direction, and to stop it at the will of the operator. (2) To control the speed of the motor at the will of the operator where a car attendant is in charge. (3) To stop the lift at each limit of travel with all loads between full load and no load. In high-speed lifts this usually involves some preliminary slowing-down device. (4) To disconnect the motor from the line and apply a brake in the event of overrunning in either direction. (5) To control a brake which will stop the car positively at each landing and hold it securely in position.

The chief components of the controlling equipment are the main and reversing switches, the accelerating devices, overload protection devices, switches and relays as required for dynamic braking, multiple-speed operation, automatic landing and the like, and suitable interlocking devices. The interlocking devices should safeguard not only against ignorance and carelessness on the part of lift-users, but also against deliberate tampering. The landing and lift-gate interlocks, which should prevent the lift being started or run with the lift-gate or any landing gate open, are specially liable to be misused. Considerable ingenuity is often misapplied to frustrating the purpose of these vital safeguards in order to suit the convenience or even to gratify the mischievous whim of some person.

Handrope Control.—The simplest form of control is akin to that used on hydraulic lifts, where a loop of rope runs the whole length of the lift shaft, one half of the loop passing through the car, and being suitably attached to the control gear at top or bottom. By pulling on the rope in the natural manner to provide

the required movement or stop, the controller is placed in the appropriate operating position. This method is obviously restricted to slow-speed operation and is now employed only on low-speed goods lifts. No electrical connection is required between car and controller. Instead of the handrope being operated directly by hand, it may be connected to a lever or handwheel in the car, an arrangement which enables the operator to deal with somewhat higher speeds.

Car Switch.—A master switch is located in the car and is generally of the semi-rotary type, connected by trailing cables to the controller. The switch is employed only for selecting the desired direction of travel and the operating speed required, all other operations being automatically effected on the control panel. A spring-operated centring device is generally provided to ensure return to 'stop' if the car attendant should remove his hand from the switch handle or lever. This is the method commonly employed where all operation is to be effected from within the car itself, by a regular attendant, or (less frequently) by a traveller acting as attendant, and it is probably the commonest type in use for office lifts and the like.

Push-Button Control.—This gives fully automatic operation, actuated by the passengers themselves. A push-button is provided at each landing for the purpose of calling the lift up or down. Only momentary depression of the button is required. Inside the car is a series of similar push-buttons, one for each of the floors to be served and, usually, an emergency 'stop' button. On momentary depression of any floor button, provided all gates are properly closed, the necessary connections are established by relays on the control panel for the lift to travel to, and stop at, the floor associated with the button pressed.

This method is particularly suitable for flats, hotels, and like premises where the traffic does not warrant the regular attendance of an operator. It is necessarily more expensive in first cost, by reason of the additional complication of the switchgear and safety devices. The controller requires the addition of a selector switch, driven from the winding engine or from the car itself, which makes the necessary connections for stopping the car at the landings. The necessary addition of the gate-interlocking device unfortunately renders the system liable to temporary derangement by the action of careless passengers in omitting to close gates. At each

floor in the lift well a 'floor direction switch' is required, the position of which is reversed every time the car passes it. This is to ensure that, when an intending passenger presses the lift-calling button on any landing, the lift will move upwards if it is below that landing, or downwards if it is at a higher floor.

The automatic system has the disadvantage that delays may be occasioned by a careless passenger forgetting to shut the gates or closing them imperfectly. It is not an advisable system to install where heavy traffic is likely, as a single passenger can commandeer the lift and pass floors where intending passengers are waiting. A simpler system of the same type provides only three buttons, 'up,' 'down' and 'stop,' which naturally requires more attention on the part of the passengers.

Space does not allow a full description of the many relay-operated devices that successively come into play during the operation of a fully automatic press-button lift, but the broad working principles are as follows :—

On pressing the starting button for any particular floor, power is applied to the motor through starting resistance, which is cut out gradually as required by relays energised by a shunt across the armature, in the case of a D.C. elevator. There may be several of these relays, coming successively into action, the last of them cutting out the series magnet coil of the motor for final acceleration. For ensuring travel in the right direction, there is a floor-controller, consisting of a drum which is revolved in unison with the main shaft of the elevator while at the same time travelling along a coarsely-threaded shaft, so that for any position of the lift there is a corresponding position of the drum. On the periphery of the drum are a series of parallel spirals of brass, with the same pitch as the thread, for 'up' and 'down' motion respectively, with brushes bearing on them. The spirals are each broken at points corresponding with the floor levels when the lift is travelling, so that the 'selected' brush breaks the circuit when it comes to the end of its spiral. Before the cage reaches the floor at which it is intended to stop, similar relays slow down the motor and finally release the brake. The whole of the power circuits are placed in the motor chamber, and operated by relays from the separate low-pressure operating circuit; this latter has press-buttons for making any circuit required, and the circuit also runs through the outside and inside gates of the cage, so that if gates are left open the circuit is broken.

A further safety device is an electromagnet excited in series with the coils of the reversing switch, which will open the main circuit if the reversing switch sticks. There are also stops near the top and bottom of the travel, where a trip in the operating circuit is actuated by the cage, in case the normal stopping gear fails to function; and a slack cable switch to prevent the cage starting if a rope has jammed. In addition to the door stops, there is a 'stop-switch' in the cage which enables it to be stopped at any moment.

In the absence of very complete diagrams of connections, it would be no easy task to connect up the parts of an automatic lift; and the methods employed vary considerably. To take an example, however, from one particular lift, the effect of

pushing a button may be followed out. It completed a circuit through a lamp and a resistance, through the 'slack-cable switch'; through the outer gate contacts, through one magnetising coil of the circuit-breaking magnet, through the inside door contacts, and the 'stop-switch' in the cage (which is normally closed, but opened when pressed); thence through the second magnetising coil of the circuit-breaking magnet (so that, the two coils being in opposition, the magnet does not move), and through the two touching contacts actuated by this same magnet; thence through another pair of contacts held together for the time being; thence along the wire common to all the floor buttons, then through the push-button we have assumed to have been closed by the operator, and thence through the magnetising coil of the circuit-making magnet for the floor to be run to (there is one for each floor); then through the appropriate (up or down, as the case may be) spiral conductor on the floor controller via the brush in connection with it and out again by the other brush; through the up (or down) segments of the stop-motion switch; through the exciting coils of the safety magnet and the reversing switch; back again through the remaining segments of these two gears, up to the limit switch, through a further resistance and lamp and so to the other pole of the supply circuit.

If any gate or door or contact in this long series is open, operation is barred. If everything is in order, then the making of the circuit causes the safety switch and the reversing switch to be energised and attract their armatures; the former completing the main circuit and the latter determining the direction of travel. At the same time, the circuit-making magnet for the desired floor attracts its armature and establishes the connections for stopping at that floor; and at the same time it completes a shorter parallel circuit which immediately enables the push-button to be released, though the gate contacts and safety devices are still in circuit. Meantime, however, all the other push-buttons are rendered inoperative until the car has come to rest and the opening and subsequent closing of the gates has restored everything to its initial condition.

Dual Control.—A combination of car switch and push-button control is frequently provided, at great first cost, where a lift must always be available, but the traffic justifies the employment of an attendant only during certain periods. Suitable means must be included to render the car push-buttons inoperative when the car switch is being used, and, at the same time, to transfer the landing push-buttons to the circuit of the floor indicator in the car.

In order to expedite the lift service in very lofty buildings, where the volume of traffic is such that a number of lifts must be provided, it is usual to arrange that each lift or group of lifts serves only a certain number of floors and runs 'express' past the others.

For example, the Greater Penobscot Building, Detroit, has lifts grouped as follows:—

6 local passenger lifts serving the basement to the 14th floor.

6 intermediate passenger lifts serving the basement, 1st, and all floors from 12th to 27th.

6 express passenger lifts serving the basement, 1st, and all floors from 26th to 34th.

- 3 shuttle passenger lifts serving all floors from 34th to 44th.
- 1 freight lift serving all floors from 2nd basement to 5th floor.
- 2 freight lifts serving all floors from 5th to 44th.
- 3 passenger lifts for a bank in the building, serving all floors from the basement to 5th floor.

The bank lift runs at 350 ft. per min., the other passenger lifts at 700 ft. per min. in the local zones and 800 ft. per min. in the 'express' zones. All the lifts are of the gearless traction type with individual motor-generators, multi-voltage control, and main motor micro-levelling.

A problem of considerable difficulty in the operation of lifts in high buildings is that of simplifying the car attendant's duties and of ensuring that a passenger waiting on an intermediate floor is served by the first available lift. Where traffic is heavy and the number of floors served is great, the most economical system is to run the lifts in definite sequence and, as nearly as possible, to a fixed time schedule. In any case, it is obviously desirable that a waiting passenger's 'call' should be transferred automatically to the nearest approaching lift, provided that the latter is not running express through the floor in question.

Many different solutions to this problem have been devised and new systems of signalling and control are continually being described in the technical press. The following are some of the principles applied, in various combinations, in recent installations:—

(1) The lift attendant operates a car switch lever which, on the second notch, causes the doors to close and the lift to start. On moving the switch back to the first notch, the car stops at the next landing and the doors open automatically. Acceleration, retardation, and levelling are effected automatically. An automatic flash lamp may be used to indicate to the attendant the proper moment for putting the car switch to 'stop.'

(2) The car may be stopped as a matter of routine at each floor in its 'local' zone: or it may be stopped only on demand, the attendant relying upon his memory or 'storing' the demands on a series of press-buttons which then stop the car automatically at the desired floors.

(3) Incoming calls from waiting passengers, who simply press the 'up' or 'down' button on their landings, cause the nearest approaching lift to stop automatically, or give a signal to the attendant who stops the car as at (2) above.

(4) Reversing gear is actuated automatically at each end of the car travel, and the car can be stopped anywhere by putting the car switch 'off.'

(5) In order to maintain a regular 'headway' or time-interval between lifts, starting signals are given to the attendants manually by a despatcher or automatically by a timing mechanism.

(6) A car operated by an attendant during rush hours may be called and operated by passengers themselves, on the press-button system, during slack hours. The speed of running is generally reduced automatically in the latter case.

(7) In order to eliminate contacts in the lift shaft for automatic stopping, steel plates may be used which induce currents in corresponding coils mounted on the lift car and actuate, through amplifying valves, the relays controlling the contactors in the switch room.

The circuits required for these and similar purposes are intricate, but they operate satisfactorily in practice; indeed, it is only by some such means that adequate lift service can be given in large and lofty buildings.

Lift car doors in this type of installation are commonly of the centre-opening sliding type operated by electrically-controlled compressed air cylinders. The outward-opening type is objectionable, if not dangerous, to waiting passengers. The average speed of a lift is materially affected by the time occupied in opening and closing the doors and, as a little observation will show, some types of levelling gear and door mechanisms are very sluggish in action. On the other hand, a fast-moving door may injure a trapped passenger by its own inertia, notwithstanding automatic safety gear. Rubber edge-flaps as used on the sliding doors of 'tube' railway carriages might be fitted advantageously on all lift doors.

Brakes.—A brake is always essential to an electric lift, and must fulfil the dual function of bringing the lift to rest quickly and without shock; and maintaining the lift in a stationary position during loading and unloading. The commonest type is the 'magnetic' brake. The flange coupling between the motor and first driving gear is provided with a flange on which two shoes, suitably lined, are pressed by the action of a spring. The brake shoe arms are also connected to the plungers of a magnet energised from the line, so that the shoes are pulled off when current is supplied to the motor, and are automatically applied when the current supply is interrupted. This brake is automatically applied in the event of any interruption to the supply, and is therefore generally fitted in addition to any other form of braking not inherently including this feature. It is the commonest type of brake employed, and is a comparatively simple design, with certain action, on D.C. supply. A.C. magnet brakes are more difficult to design for equally effective operation and many types have been evolved, including a small motor designed to remain across the line with the rotor stalled, and long-stroke types with dashpots to secure steady closing. Variable reactance in the magnet circuit has also been used to produce a gradual application of the brake as the car switch is moved towards the 'off' position. One disadvantage of A.C. brakes, and, in fact, of all A.C. control gear, is the tendency to 'hum.' Copper oxide rectifiers have been used to provide D.C. for brake and control gear in some A.C. lift installations.

Dynamic Braking is sometimes incorporated in D.C. installations, the shunt field of the motor being connected to the line and partially or fully energised therefrom, while the rotating armature is shunted by a resistance. The motor then operates as a generator and the energy of rotation is dissipated as heat, the armature experiencing an opposing torque during the energy transformation. This system alone will not bring the lift to rest, particularly if the load is overhauling, since the torque diminishes continuously with reduction of speed, but it materially reduces the speed and thus facilitates smooth stopping by a magnet brake.

On A.C. systems a similar dynamic braking effect can be provided where a two-speed motor forms the driving unit. The low-speed winding is connected to the supply while the motor is running above the synchronous speed of this winding, causing the motor to act as a self-excited induction generator, returning energy to the line, and to experience a resisting torque until its speed falls to the synchronous speed of the low-speed winding.

Lift Landing Gear.—If a lift car is to be brought accurately to rest, level with the floor landing, by manual operation of the controller, it is essential that the speed be reduced some time before the floor is reached. Even so, the car will often stop short of, or overshoot the landing; ‘inching’ is then required to bring it to the correct level, and this places heavy duty on the switchgear, besides additional shock and bending on the hoisting ropes. The higher the speed of travel of the lift, the greater the difficulty in securing accurate landing by manual control, and the more serious the decrease in average speed resulting from retardation in preparation for stopping, and loss of time in ‘inching’ up or down to the floor level.

Various methods have been devised for stopping the car automatically at the correct level, and the use of one or other of these is almost essential to the efficient operation of high-speed lifts.

The Westinghouse automatic ‘inductor’ system of control uses inductor plates mounted on the counterweight guide rails to actuate slowing-down and stopping inductor switches mounted on top of the lift car. There is no mechanical contact between the fixed plate and travelling switch, but when the latter comes in front of the inductor plate the switch magnet is attracted, thus opening a relay circuit. Though the liftman can, at any time, assume complete control, the car is normally put under the control of the automatic gear as it approaches the floor at which it is to stop. The first and second slow-down inductor plates then reduce the car speed in two stages, and the stopping inductor plate brings it to rest.

In some systems 'automatic levelling' or 'micro levelling' is provided, *i.e.* the lift is stopped level with the floor and this level is maintained, notwithstanding elastic stretching or contraction of the ropes due to increase or decrease in the total load or differences in the amount of braking applied under different conditions of load and running. In other cases 'automatic landing' is provided, *i.e.* the car is stopped level with the floor, but any subsequent changes in level are not corrected. Both systems are widely used. Automatic or micro levelling is very desirable as the main consumption of energy is in accelerating the car from rest. False stops are eliminated, together with their associated 'corrective' restarting which, apart from being unpleasant and irritating to passengers, wastes time and energy and increases wear and tear. One method employed consists in attaching the housing of the main magnet brake to a worm wheel shaft driven by a small auxiliary motor and worm. The main brake shoes operate normally, but if the levelling is inaccurate when a normal stop is made contacts in the neighbourhood of the landing are closed by the car, starting the auxiliary motor and causing it to drive the main motor shaft through the main brake blocks acting as a friction clutch, until the exact level is reached. Subsequent loading and unloading of sufficient magnitude to alter the stretch of the ropes are similarly dealt with so that the platform level is maintained. Operation of the main motor disconnects the auxiliary motor. Threshold lighting, to show passengers the 'step,' is unnecessary where automatic levelling is in use.

798. Goods Lifts.—Much that has already been said concerning passenger lifts is applicable to goods lifts, particularly as regards the general arrangement, method of drive, control, etc. The car is obviously of simpler construction than for a passenger lift, and, in general, the running speed is lower, particularly in cases of small total travel. The choice of control, whether handrope, car switch, or push-button, will depend entirely upon the service required, while the addition of such refinements as automatic levelling will depend upon the nature of the loads to be carried and the precision and care with which they must be handled. In general, the suitability of the car and loading arrangements for the loads to be handled is of greater importance than the provision of high speeds; and a much wider range of loads is met with than in passenger lifts, ranging from about $\frac{1}{2}$ cwt. in 'service lifts' to several tons

for large industrial lifts. Typical data are given in Table 171, § 800.

799. Estimation of Lift Capacity Required.—In the case of goods lifts, this is comparatively simple, being mainly decided by the maximum load it is desired to transport and the speed of hoisting required. For passenger lifts, however, this is a matter of great difficulty, particularly in the case of office lifts. Where an office building accommodates a large number of workers with different times of arrival and departure, there will be periods of rush traffic which will decide the lift capacity required. Pronounced peak loads also occur in the services for shops, stores, and restaurants.

In general, it is preferable to install several lifts of small capacity rather than one of large capacity, owing to the greater flexibility obtained and the increased speed at which traffic may be handled. In lofty buildings it is good policy to reserve one or more lifts for 'express' service, stopping only at floors in the upper half of the building.

The maximum traffic capacity is greatly increased if the winding engine operates with the maximum permissible rate of acceleration and is adapted for automatic floor levelling. Correct location of the lifts in relation to the disposition of the offices is also a matter of importance. It is usual to allow about $2\frac{1}{2}$ to 3 sq. ft. of floor area in the car per passenger.

A valuable paper by Marryat* includes a reasoned treatment of the question of lift capacity and presents an empirical formula from which the lift capacity may be estimated for London offices or similar service.

An average of one stop per 42 ft. of lift travel may be allowed, together with a total delay at each stop of 12 secs. From these assumptions

The time of one circular trip (up and down)

$$S = \frac{60 \times 2T}{R} + \frac{2T \times 12}{42} \text{ secs.}$$

$$= 0.57T \left(\frac{210 + R}{R} \right) \text{ secs., approx.,}$$

where T = total travel of lift in one direction, in ft.;

R = running speed of the lift, in ft. per min.;

and the number of circular trips per hour is then $3600/S$.

* 'Electric Passenger Lifts,' H. Marryat, *Jour. I.E.E.*, Vol. 62, p. 328.

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Marryat's formula (*loc. cit.*) is—

Lift capacity (number of passengers) required in a London office building = $\frac{9.6A}{NL}$

where A = rental floor area above first floor, in thousands of square feet.

N = number of circular trips per lift per hour, inclusive of stoppages, computed as above.

L = the number of lifts installed.

This provides for carrying a maximum traffic of 9.6 persons per hour for every 1 000 sq. ft. of rental floor area above the first floor, *all in one direction*.

The procedure is to estimate the total peak traffic to be handled (*i.e.* 9.6 A); the number of circular trips per lift per hour, *i.e.* N , as shown above; the frequency of service required, *i.e.* choosing a value of L ; and then to calculate from the formula the number of persons to be provided for in the lift. Should the calculation require too large a capacity, a greater number of lifts should be provided.

EXAMPLE.—Suppose that an eight-story building has 80 000 sq. ft. of rental floor area on the six floors above the first floor. The maximum traffic to be handled would be about 9.6×80 or 768 persons per hour. Suppose that a lift speed of 400 ft. per min. be adopted, that the total height of travel is 100 ft., and that there is a stop causing 12 secs. delay every 42 ft. of travel on the average. Then the time per round trip is: $0.57 \times 100[(210 + 400) / 400] = 87$ secs., or $2\ 600 / 87 = 41.4$ circular trips per hour. Two lifts would probably give an adequate service, and the capacity of each would have to be $768 / (2 \times 41.4) = 9.27$, or, say, 10 persons.

If lifts hold more than 10 persons, or are not well proportioned and arranged as regards doors and landings, the delay at stops may exceed 12 secs. average, inclusive of accelerating and decelerating.

The effect of the stop delay is to decrease the *extra* saving arising from the use of higher speeds as the speed increases—see curve A in Fig. 389. With terminal stops only, curve A changes to curve B , other factors remaining constant, which shows the advantage of non-stop ('express') lifts in high buildings. The dotted curve C corresponds to the limiting case of constant speed throughout with no delays, a condition which is unobtainable in practice because some time must be allowed for loading, accelerating, retarding, and unloading. The advantage of eliminating intermediate stops is shown more clearly perhaps by comparing curve b with curve a , these curves showing the relative passenger-carrying

capacity per hour at various speeds, taking the capacity at 300 ft. per min. as 100 in each case; and the curves *a*, *b* corresponding to *A*, *B* respectively.

In lofty buildings, higher average speeds can be obtained, and at lower costs, by eliminating intermediate stops than by raising the running speed.

800. Typical Lift Installations.—Table 171 and Fig. 390 are based on data kindly supplied to the authors by Messrs. Marryat & Scott, Ltd. (London). The data relate to a selection from the passenger and goods lifts installed by that firm, and are a useful

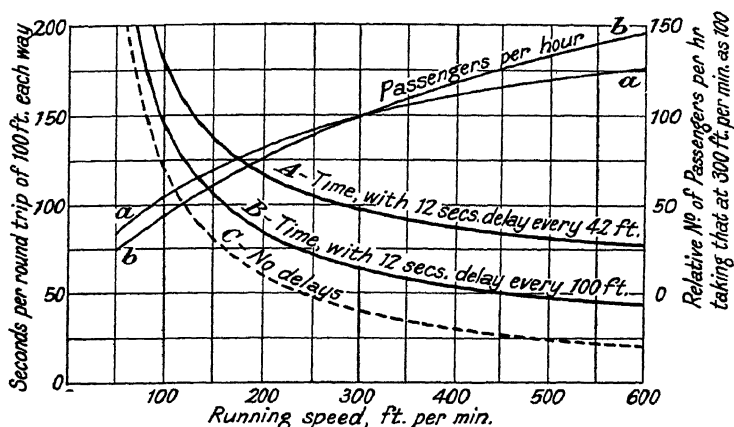


FIG. 389.—Showing effect of stop-delays in limiting the advantage derived from higher lift speeds.

guide to recent practice. It must be clearly understood, however, that they do not necessarily represent the best results that could now be obtained in a new installation.

801. Energy Consumption of Lifts.—As with other forms of transport, it is difficult to give any precise data on the energy consumption, since the conditions of load and service vary so much between different installations and are never constant in any one installation. Average values over long periods of time are of some value, but, while an exact record of actual energy consumption can be taken, it is seldom practicable to keep a corresponding census of the loads carried, particularly in passenger service. Consequently, no exact value can be determined for the overall efficiency.

TABLE 171.—*Electric Passenger and Goods Lifts.*

(By Courtesy of Messrs. Marryat & Scott, Ltd.)

Premises.	Load.		Speed Ft./ Min.	Travel Ft.	Energy Supply to Motor.			Motor.		Control C.S. = car switch P.B. = push- button H.R. = hand rope Dual = C.S. and P.B.	Remarks.
	Weight Cwt.	No. of Persons (Average 140 lb. Each).			Volts.	D.C. or A.C.	Cycles per Sec.	H.P.	Type G = compound S.C. = squirrel- cage S.R. = slip-ring R = repulsion I.R. = induction repulsion V.S. = variable speed A.C. commtr.		
Aquarium theatre and café	25	20	200	34	460	D.C.	—	23	G	C.S.	—
Offices	20	16	300	53	480	D.C.	—	29	G	C.S.	—
Cinema	15	12	250	66	460	D.C.	—	18	G	C.S.	—
Showrooms	15	12	200	65	400	D.C.	—	15	G	C.S.	—
Shops	12½	10	240	75	530	D.C.	—	14	G	Dual	—
Offices	10	8	300	85	200	D.C.	—	14	G	C.S.	—
Royal Palace, India	10	8	120	30	220	D.C.	—	6	G	P.B.	—
Offices	10	8	350	65	220	D.C.	—	16	G	C.S.	—
Offices	9	7	250	80	460	D.C.	—	10	G	Dual	—
Offices	7½	6	120	45	440	D.C.	—	4½	G	P.B.	Fed from rectifier
Private residence	3	2-3	70	33	220	D.C.	—	1½	G	P.B.	—
Cathedral Tower (London)	15	12	350	190	400	3 ph.	50	25	V.S.	C.S.	—
Police station	10½	8-9	160	70	350	3 ph.	50	10	S.R.	Dual	—
Hospital stretcher lift	10	8	90	38	400	3 ph.	50	5	S.R.	P.B.	—
Stores	6	4-5	80	15	110	3 ph.	60	2½	S.R.	P.B.	—

Offices	2-3	110	30	200	50	2½	I.R.	P.B.	
Offices	8	115	48	200	50	6	I.R.	P.B.	
Vegetable auction rooms	50	100	50	480	—	24	C	C.S.	Auto-levelling
Garage	50	40	45	200	—	10	C	C.S.	—
Mineral water bottling	36	60	45	200	—	10	C	P.B.	Auto-levelling
Dye works	30	120	52	230	—	16	C	P.B.	Auto-levelling
Brewery	20	50	35	400	—	5	C	H.R.	—
Printers	15	150	64	410	—	10	C	C.S.	—
Wine stores	10	30	10	220	—	3½	C	Single lever	Unbalanced platform hoist
Furniture warehouse	10	90	21	440	—	4½	C	P.B.	Fed through rectifier
Drapers	8	80	12	240	—	2½	C	P.B.	Unbalanced platform hoist
Musical instruments	7	60	11	530	—	2½	C	P.B.	—
Factory	6	130	29	200	—	4½	C	P.B.	—
Dye works	3	120	51	230	—	2	C	P.B.	—
Furniture factory	40	60	15	415	50	10	S.R.	P.B.	—
Foundry	40	30	15	400	40	15	S.R.	P.B.	—
Garage	25	20	15	400	50	10	I.R.	H.R.	Unbalanced
Furniture depository	20	50	60	400	50	5	S.R.	C.S.	—
Oil warehouse	10	60	33	500	50	2½	S.C.	P.B.	Through 2 000 V
Piano showrooms	9	250	70	380	50	12	V.S.	P.B.	trsf.
Furniture factory	7½	80	31	415	50	3	S.C.	P.B.	—
Paint factory	6	30	12	400	50	3	S.C.	H.R.	—
Hospital	5	60	12	400	50	5	S.C.	P.B.	—
Motor car; lorries	80	20	17	200	50	20	S.R.	C.S.	Unbalanced
Railway station	30	70	13	220	50	10	P.B.	P.B.	Unbalanced
Stores	15	70	91	200	50	3½	I.R.	P.B.	Auto-levelling
Meat storage	10	60	18	400	50	8½	R.	P.B.	—
Motor cycle showrooms	5	15	11	200	50	3	I.R.	P.B.	Unbalanced platform hoist

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H. C. Crews* gives the following consumption data for lifts on various kinds of service :—

Tall office building, very busy	1 100 kWh per year.
Busy office block	614 " " "
Hospital bed lift	404 " " "
Busy 15-cwt. lift in residential block	666 " " "
Clothes warehouse, busy	563 " " "
Cotton warehouse, goods only	355 " " "

H. Marryat† gives the average annual consumption of 50 electric lifts in Westminster (London) as 1 060 kWh, including that used for car lighting.

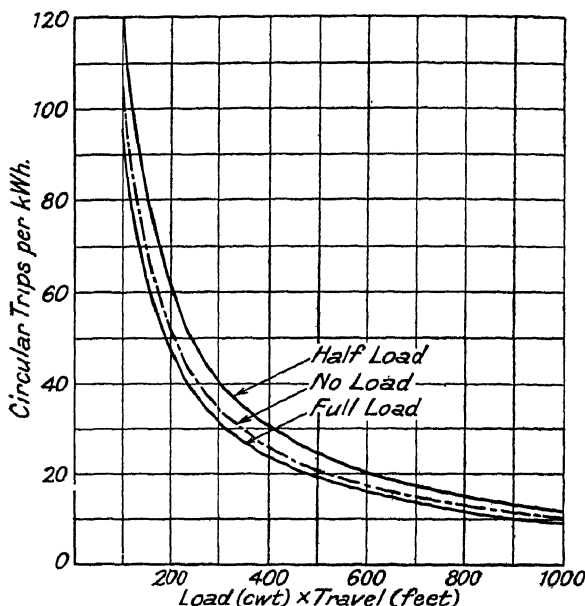


FIG. 390.—Energy consumption of electric lifts.

For estimating purposes, the chart in Fig. 390, reproduced by courtesy of Messrs. Marryat & Scott, Ltd., is useful.

To obtain the number of circular trips per kWh :—

(1) Multiply the load (cwt.) by the travel (feet) and find this point on the horizontal scale, dividing the product by 10, or 100, etc., to bring the point within the range of the horizontal scale.

(2) Move vertically to the appropriate curve.

(3) Then move horizontally to the vertical scale, and take the reading; dividing

* *Jour. I.E.E.*, Vol. 62, p. 346.

† In a paper before the Association of Supervisory Electricians, 1915.

by 10, or 100, etc., where this has been done in (1). The result is the number of circular trips per kWh for the particular fraction of load concerned.

EXAMPLE.—With a load of 30 cwt. and a travel of 100 ft., what is the number of circular trips per kWh at full load?

(1) $30 \times 100 = 3\,000$. Divide by 10 to bring the value within the scale, giving 300.

(2) From 300 on the horizontal scale move vertically to the 'full-load' curve.

(3) Move horizontally to the vertical scale, reading 31.8. Divide this by 10, which was the divisor used in (1), giving 3.18.

Then 3.18 circular trips can be made per kWh at full load with a load of 30 cwt. and a travel of 100 ft.

802. Electric Stacking Machines.—These are really portable electric goods lifts. A low trolley frame on wheels carries an electric motor and suitably driven winding drum, together with a vertical framework up which the lifting table is raised by ropes passing from the winding drum over head pulleys and down to the table. Connection is usually made by trailing cable to conveniently placed power plugs and an automatic magnet brake is fitted to maintain the table and load in position when the current supply is interrupted or fails.

Loads up to about 1 ton are regularly lifted over heights up to 20 ft. at speeds ranging from 60 to 80 ft. per min.

803. Conveyors.—For many continuous manufacturing operations, loading and unloading, cleaning of materials and the like, there is a great variety of 'conveying machinery' in use by which material and articles are pulled, pushed, or shaken along or lifted on straight paths. The arrangement of such devices is purely of a mechanical nature and any convenient form of power drive may be employed. For permanent installations, in factories and warehouses, electrical drive offers many advantages over other methods, being flexible, convenient and clean, and providing any desired devices for the safe and efficient control of the mechanical equipment. Interlocking devices may be readily installed, ensuring the starting-up of the components of a complicated system in any predetermined sequence and providing for the stopping of the whole installation in the event of failure of any member of the installation. The variety of the mechanical installations and the wide range of work dealt with are such that no useful data can be given regarding the power consumption of their electrical equipment. In most conveyor installations the greater part of the total load is the frictional resistance of the conveyor itself and this varies indefinitely with the design, construction, and dimensions.

Vertical-Conveyor Hoist.—For dumbwaiter service in taking crockery, food, etc., to and from various floors of a restaurant or hotel and the kitchen, a special type of continuous hoist may be used consisting of two vertical chain conveyors. The chains carry slats, and the faces of two conveyors form the sides of the lift well. At intervals on each chain there are angle-iron brackets. The brackets on the two chains are opposite to each other and the trays rest upon them. On arrival at the kitchen, trays are shifted on to a horizontal belt conveyor by a rotating arm. In a particular case a 5 H.P. 850 r.p.m. geared motor drives a hoist of this type serving 6 floors. An emergency stop button is provided at each floor. When the conveyor is running reversed to deliver food, the stopping floor is selected by a press-button switch in the kitchen.

804. Escalators.—The escalators or moving stairways, now used in many underground railway stations instead of lifts, consist essentially of endless chain conveyers with steps attached to the links. In recent installations the steps are of steel plate with wooden tread and riser, and are carried between two main driving chains, the driving sprocket being driven, through worm and chain reducing gear, by a D.C. compound-wound interpole motor with speed variation by field control. Each step is mounted on a four-wheeled carriage, the two front wheels being on rails of a narrower gauge than those which carry the two rear wheels. At the top and bottom landings the two sets of rails are in a horizontal plane, and the steps therefore form a moving horizontal platform. At the commencement of the rise, in the case of an 'up' escalator, the inner rails are carried forward horizontally, for a distance equal to the wheelbase of the step carriages, from the point at which the outer rails commence to rise. Thereafter the rails rise, parallel to each other, at the inclination of the stairway. The effect of this is that the moving platform 'generates' steps as the rails change from the horizontal to the incline. The top of each step remains horizontal throughout the rise, and the rise of each step disappears as the tread comes level with the top landing. The front of each step is curved to maintain close contact with the back of the next one throughout the stairway; and the back of each step is undercut to admit the front edge of its neighbour when the carriages are returning, inverted on the underside of the escalator. Some of the latest escalators have roller bearings throughout, with the exception of bakelite step-wheels with graphitised bores.

An escalator installation comprises at least two stairways, one running upwards, the other down. A third, stationary stairway placed between the escalators provides economically for those who dislike moving stairways and, at the same time, it employs usefully a clearance space which greatly facilitates the installation and maintenance of the escalators. In stations with heavy 'rush' traffic, one way in the morning and the opposite way in the evening, it is advisable to install 'up' and 'down' escalators and a reversible escalator between them. The central escalator can be used as a fixed stairway during periods of light traffic, and as either an 'up' or a 'down' escalator during 'rush' periods.

TABLE 172.—*Power to Drive Escalators.*

Rise of Escalator. Ft.	Sloping Length of Stairway.* Ft.	Horse-power of Main-drive Motor.† H.P.
28	68	30
30	67½	—
32	72	30
34	76½	30
38	85½	40
42	94½	40
54	122	60-65

*Inclination to horizontal = 26° (approx.).

†Two motors (one being spare) of this H.P. for each 'up' or 'down' escalator.

The slope of the inclined portion of an escalator can be varied within considerable limits; generally, it is about 25° to 30° to the horizontal. The principal limitation to the slope is the danger of passengers being subject to giddiness when looking down a long escalator; also, the slope must not be such that a passenger who slips or falls is in any danger of rolling. With a slope of 25°, the length of the incline is $1 / \sin 25 = 1 / 0.4226 = 2.366$ ft. per ft. of rise. Table 172 gives typical data based on some of the escalators in London railway stations.*

The estimation of the power required to drive escalators is discussed below. In making these calculations it is advisable to err on the side of liberality owing to the serious consequences of motor breakdown in this service. Also, the starting effort demanded by an escalator is high (the total length of the escalator

*Rises up to 90 ft., linear speeds up to 180 ft./min. on a slope of 30°, and motors up to 150 H.P. are provided in some of the latest (1939) installations.

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chain being often 250 to 300 ft. or more); and, in the case of a reversible escalator, the frictional losses are temporarily increased considerably by the reversal of the direction of travel.

Though the speed of lifting of an escalator is relatively low (90-150 ft. per min. on a slope of 30° corresponds to a lift of 45-75 ft. per min.), the machine is continuously in motion and completely eliminates the time lost in waiting for, loading and unloading lifts. It effects a great reduction in the station staff required, and it deals continuously with even the heaviest traffic without causing any serious reduction in the rate of flow.

If the height of each step be 9 ins., the rate of lift 45 ft./min., and each step be occupied by one passenger, then $45 \times 12 / 9 = 60$ passengers per min. or 3 600 per hr. are carried. During rush hours many of the steps are occupied by two people and there is generally a line of people walking up one half of the moving stairway, thus further increasing the maximum traffic capacity.

An escalator of 40 ft. lift with 9-in. steps may carry $2 \times 40 \times 12 / 9$ or, say, 107 persons at a time (two on each step). To lift this load at the rate of 45 ft./min., allowing 150 lb. per person, requires *theoretically* $107 \times 150 \times 45 / 33\ 000 = 22$ H.P. With an overall mechanical efficiency of 55 %, a motor of 40 H.P. would be large enough, bearing in mind the fact that the escalator would never be loaded to this extent for long at a time. If the mechanical efficiency were 70 % under full-load conditions a $22 / 0.7 = 31.5$ H.P. motor would suffice, but the margin afforded by a 40 H.P. machine is reasonable for this service.

The longer the escalator, other factors being constant, the higher the H.P. of the motor required, for, although the rate of delivery of the passengers be constant, they are raised through a greater height at the same rate and the H.P. is therefore proportionately increased. Actually, the mechanical losses are also greater in longer escalators.

Allowing an average weight of 150 lb. per person, the H.P. required to drive an escalator may be estimated from the formula:

$$\text{H.P.} = \frac{N \times 150 \times H}{33\ 000 \times \eta} = \frac{NH}{220\eta} \text{ horse-power,} \quad (1)$$

where N = number of persons carried per min.
 $= 12pd/r$ (the symbols p , d , r having the meanings given below).
 H = height of lift, in feet.
 η = overall mechanical efficiency (as a decimal, *not* per cent.).

Alternatively, the horse-power may be calculated from—

$$\text{H.P.} = \frac{p \times n \times 150 \times d}{33\ 000 \times \eta} = \frac{pnd}{220\eta} \text{ horse-power,} \quad (2)$$

where p = number of persons per step.
 n = number of steps on the sloping part of the escalator
 $= 12H/r$.
 H = height of lift, in feet $= l \cdot \sin \theta$.
 l = length of slope of escalator, in feet.
 r = rise of step, in inches.
 d = rate of lifting, in ft./min.
 $= V \cdot \sin \theta$.
 V = rate of travel of escalator, in ft./min.
 θ = angle of inclination of stairway to horizontal, in degrees.
 η = overall mechanical efficiency (as a decimal, *not* per cent.).

Choice between these formulæ is purely a matter of convenience.

EXAMPLES.—(1) Suppose an escalator runs at 90 ft./min. on a slope of 25° through a height of 40 ft.; the height of each step being 8 ins. and the width sufficient to accommodate 2 persons; and the overall mechanical efficiency 0.65.

The rate of lifting $= d = V \cdot \sin \theta = 90 \sin 25 = 90 \times 0.4226 = 38$ ft./min. (approx.).

The number of steps in the escalator $= n = 12 \times 40 / 8 = 60$.

The number of persons carried per min. $= N = 12pd/r = 12 \times 2 \times 38 / 8 = 114$.

Using formula (1): H.P. $= (114 \times 40) / (220 \times 0.65) = 31.8$ horse-power.

Using formula (2): H.P. $= (2 \times 60 \times 38) / (220 \times 0.65) = 31.8$ horse-power, as before. A 40-H.P. motor would probably be chosen.

(2) An escalator runs at 180 ft./min.; slope 30° ; height 90 ft.; mechanical efficiency 0.75; $r = 8$; $p = 2$. Then $d = 90$ ft./min.; $n = 135$; $N = 270$; and H.P. $= 147$.

Most of the power consumed by an escalator under average traffic conditions goes to drive the escalator itself. The overall mechanical efficiency may be in the neighbourhood of 65 to 75 % when the escalator is fully loaded, but this condition is fulfilled only under exceptional circumstances and then only for a short time. It is doubtful whether any escalator actually carries more than half its traffic capacity in any single hour; and 10 to 15 % is about the average daily utilisation factor, *i.e.* 720 to 1 080 passengers per hr. for an escalator capable of carrying 7 200 per hr. with two persons on each step. At such low loadings the overall efficiency, reckoned on the passenger load carried, is relatively low, but the escalator may still be the most advantageous method of dealing with the traffic, owing to its continuous availability, virtual elimination of labour cost, and instant capability of dealing with rush traffic. How little the average passenger load affects the energy consumption is shown by the fact that, during certain tests, with traffics ranging from 250 to 500 passengers per hr. each way, the power consumption was about 9.6 kW for the 'down' and 10.8 kW for the 'up' escalator, or say $12\frac{1}{2}$ % more

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for the up than for the down traffic. With a heavy 'down' load an escalator may consume little or no current, but it is generally not worth while to make any provision for regenerative braking.

Allowing 150 lb. per passenger and assuming the escalator itself to be perfectly balanced, the energy consumed per 100 passengers per ft. rise is given theoretically by

$$100 \times 150 \times 1 / 2 \text{ } 656 \cdot 4 \text{ (§ 52, Vol. 1) } = 5 \cdot 65 \text{ Wh approx.}$$

Actually, the consumption is higher, owing to the energy required to drive the escalator itself, and the Wh per 100 passengers per ft. rise increases rapidly as the number of passengers per hr. decreases. The figures in Table 173 may serve as a general guide.

TABLE 173.—*Energy Consumption of Escalators.*

No. of Passengers per Hour.	Wh per 100 Passengers per Ft. Rise.
—	5·65 (theoretically)
1 500	20 to 25
1 000	30 to 35
750	35 to 45
500	50 to 60
250	100 to 120

It is generally convenient to place the driving motor of an escalator in a chamber below the top landing, gearing it down to the end sprocket of the escalator chain through a double-reduction worm and spur or chain gear. The total reduction required between a 450 r.p.m. motor and a 90 ft./min. escalator is about 39 : 1. In the case of very long escalators, it may be advisable to place a second driving sprocket about half way down the tunnel, connecting this mechanically to the top drive by a propeller shaft with bevel gears at each end. In view of the importance of continuity of service, two motors may be installed, one being supplied with current while the other is driven idle but ready for immediate service; with modern plant this precaution is hardly necessary. One or two idler sprockets, meshing with the escalator chain and kept 'floating' by a compression spring, relieve the driving sprocket of one-half or two-thirds of the weight of the escalator. Chain drives from the main sprocket shaft

actuate the moving handrails and landing 'shunts' (if any). The moving handrail is an obvious necessity, and consists of a reinforced rubber band driven by friction wheels. A landing 'shunt' is required only if passengers leave the escalator at the side; it now generally consists of a hardwood skirting board arranged diagonally across the end of the landing; sometimes it consists of one side of an endless rubber belt running round end pulleys with vertical axes. In either case, the 'shunt' helps to scrape passengers off the escalator should they remain on it until the 'shunt' is reached. The latest escalators generally discharge passengers straight ahead, a metal comb then taking the place of the shunt. To provide for rapid stopping in case of emergency, switches, placed behind paper discs in boxes at each end of the escalator may be arranged to trip the motor circuit-breaker by means of the no-volt release.

The cleat-type escalator uses a lighter type of stairway, with wooden treads attached to a chain instead of the relatively heavy carriages employed in a step-type escalator. The angle of rise of a cleat-type escalator is generally about 25° to the horizontal. In a certain case a 24-in. cleat escalator driven at 90 ft. per min. by a 12 H.P. motor raised 3 400 people per hr. through a height of 25 ft. Assuming an average weight of 150 lb. per person, the useful work done = $3\,400 \times 150 \times 25$ ft.-lb. The energy expended = $12 \times 33\,000 \times 60$ ft.-lb. Hence the mechanical efficiency = $100 (3\,400 \times 150 \times 25) / (12 \times 33\,000 \times 60) = 53.6\%$, assuming the motor to be fully loaded.

Though the principal application of escalators will probably continue to be in underground railway stations, their use should be considered wherever a continuously available means of transporting a variable passenger load through a small or medium height is required.

805. Lifting Magnets and Allied Apparatus.—The magnetic properties of a solenoid find many practical applications. The use of magnets in control apparatus for the operation of switches, relays and the like, are dealt with in Chaps. 15, 16, Vol. 1, and the present notes are confined to the heavier types of electromagnets which operate as lifting magnets proper or in a comparable capacity. These include lifting magnets replacing mechanical hooks and slings; magnetic chucks as machine tool accessories; magnetic clutches, for the connection and disconnection of driving and driven machinery;

and magnetic separators, for the separation of the magnetic and non-magnetic components of a mixture.

Lifting magnets are used with cranes of all types for the lifting of magnetic iron and steel. They are merely powerful electro-magnets of appropriate mechanical and electrical design, and they offer many advantages of convenience and speed over the use of slings when loose material or awkwardly shaped articles are to be handled. Ferrous materials which are non-magnetic, such as manganese-steel, hot invar steel, and other non-magnetic alloys, cannot be held by a magnet.

The other applications of electro-magnets, such as to chucks, clutches and separators, involve different mechanical arrangements adapted to their particular purposes, but the basic principles are the same in all cases. Notes on these applications are given in §§ 807-809.

806. Lifting Magnets.—The outstanding feature of the lifting magnet is that it dispenses with the use of slinging devices. This saves time and labour in securing and releasing the load and thus enables the crane performance to be increased. There are other advantages, such as the ability to deal with work of irregular or awkward shape, or in a condition where handling would otherwise be difficult, *e.g.* hot metal; also the possibility of 'fishing' for, and securing, articles under water without the aid of divers. Loose material, such as heaped scrap, can be lifted economically by means of a magnet, provided that there is no risk of damage by material which may fall from the outside of the 'cluster' in transit.

Direct current is required for the excitation of lifting magnets, but where sufficient work is available for a lifting magnet, it will frequently prove advantageous to install a motor-generator for the necessary conversion from A.C. to D.C.

Essentially, a lifting magnet comprises a winding, or windings, arranged with suitable poles and a magnetic circuit, the whole being constructed very robustly to withstand rough handling. The pole arrangement is influenced by the nature of the load. Three main types are in use: the circular, in which an annular coil is disposed between a solid centre pole and an outer annular pole; the rectangular type, and the bipolar type. The circular pattern is best adapted for handling loose metal and scrap, and for general work; the rectangular type is more applicable to the lifting of plates and sheets; and the bipolar type is specially suited to dealing with long

narrow objects, such as section bars and billets. Two circular-type magnets may be attached to the extreme ends of a triangular support, which is suspended from the crane hook at its apex, and this combination forms a useful device for the handling of large plates or sheets.

A peculiarity of lifting magnets is that the load which can be lifted by a given magnet and power depends on the mechanical nature of the load or, more particularly, on the presence of air-gaps in the material to be lifted. The presence of even the smallest air-gap reduces enormously the total flux obtained from a given winding and given current. The maximum load under given conditions can be carried when the load is a solid piece of material, such as a billet, bar or single plate, the surface of which makes close contact with the pole pieces. Any surface irregularities much reduce the load which can be retained on the magnet face. Thus, a given magnet will lift a smaller weight of pig iron than it will of rolled sheet steel, and yet again a much smaller weight of scrap, turnings or plates, apart from any influence of the actual magnetic permeability of the metal lifted.

The figures in Table 174 indicate the *approximate* carrying capacity of lifting magnets at various power consumptions:—

TABLE 174.—*Capacity of Lifting Magnets.*

Power Consumption. kW.	Net Weight of Magnet. Lb.	Approximate Carrying Capacity, in lb.			
		Pig Iron and Forging Waste.	Turnings or Shot.	Small Pieces.	Massive Blocks.
1	450	110	175	300-400	4 000
3	2 000	450	850	1 000-2 000	18 000
5	3 100	650	1 200	1 600-2 800	32 000
7.5	4 400	1 000	1 550	2 200-3 300	50 000

A rough general guide is that magnets will hold up to about 5 lb. per watt consumed, for solid loads. Small magnets are relatively more efficient than large ones, by reason of the greater mechanical strength required in the larger sizes. For loads of a solid nature, magnets may be estimated roughly on the following lines:—

Small magnets will carry up to 20 times their own weight;

Medium sizes, say up to 3 ft. dia., 10 times their own weight;

Large sizes, say up to 5 ft. dia., 5 to 7 times their own weight, and about 10 % of these loads can be handled where scrap is lifted.

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The load which can be directly supported on a magnet is given by

$$W = AB^2/72 \cdot 13 \times 10^6,$$

where W = load supported, in lb. per pole.

A = pole face area, in sq. in.

B = flux density in the pole, in lines per sq. in.

The total flux N is AB and the flux in the object lifted may be taken as that in the air-gap. A leakage coefficient of 1.25 may be assumed, and the flux density in the body is then $1.25 N/a$, where a is the body area (perpendicular to magnetic path) in sq. in.

With a flux density of 80 000 lines per sq. in. (magnet steel) a load of 3 tons could be carried by a circular magnet of the following pole face dimensions:—

Dia. of central pole, 7 in.

Internal dia. of outer pole, 15 in.

External „ „ „ 16½ in.

It is usual to cover the pole faces by a thin sheet of non-magnetic material (brass) to prevent the sticking of small particles, and ensure instantaneous release of load when the magnet switch is opened.

Some means must be adopted to protect or 'armour' the field winding against the roughest of handling and yet to provide sufficient cooling. One effective method is to employ an aluminium winding (giving lightness) in which the insulation between turns and layers is provided only by the oxide film on the strip. This provides sufficient insulation for the low potential difference between the adjacent turns and is conducive to good cooling by making the winding practically solid metal as regards the conduction of heat. Air passages may be provided around the winding with vents through the top of the magnet casing, to assist in carrying away the heat. Sometimes forced ventilation is provided by the incorporation of a self-contained electric fan.

Drum controllers are commonly used for the operation of lifting magnets, with a demagnetising notch to ensure a quick release of the load. Where a variation in the lifting capacity is desirable, the controller may be arranged to provide a variable current. It is thus possible to pick up a number of plates one at a time and one below the other, and to release them one at a time. This enables plates to be collected from different parts of the shop and to be deposited at different machines at will with a minimum of time and labour.

The following particulars indicate the possibilities of a lifting magnet in submarine salvage work: A 36-in. dia. magnet, weight 10 cwt., and taking 18 A at 220 V, averaged 5 cwt. per lift in salvage from a dock with water 20 ft. deep. About 100 tons of material was hoisted in 5 days.

807. Magnetic Chucks.—Magnetic chucks are among the most useful of machine tool accessories. Their use often enables clamps to be dispensed with, thus saving time and labour; and they afford means of securing small and thin articles of iron and steel where mechanical methods of fastening would be inconvenient or impossible. Furthermore, the elimination of clamps enables a larger number of articles to be accommodated over a given area, a matter of importance in repetition work.

The basic principle of construction is that the flat holding surface of the chuck is arranged to contain or consist of magnetic poles of opposite polarity, the poles being separated by non-magnetic material (usually brass or lead) to maintain a physically continuous surface. One or more magnet windings are contained in the body, and this steel casing, which is bolted to the machine table, or supported on the machine spindle in the usual manner, is arranged to form part of the magnetic circuit. With energy supplied to the windings, a leakage field is set up across the non-magnetic material separating the poles; by suitable disposition of the pole pieces it is possible to cover most of the surface with this field. When a magnetic body is placed on the surface, provided that the contact area is sufficient to cover more than one pole, the flux finds an easier path through the article, which then becomes attracted to the chuck surface like a magnet 'keeper.'

The face of the chuck may be circular or rectangular, according to whether it is to be used on, or as, a rotating face-plate or on the table of a machine having rectilinear motion. The energising magnet may consist of a single magnet or several magnets, according to the shape and size of the chuck; several 'teeth' or poles may be energised from each winding, and their arrangement and shape are of infinite variety, adapted either for holding special work or for obtaining as uniform a magnetic field as possible over the chuck face. The space between adjacent parts of opposite polarity varies from $\frac{1}{8}$ to $\frac{5}{8}$ in., according to the size of the chuck. It is essential that the working face be water- and oil-proof to enable the appliance to withstand the usual workshop conditions of usage. The magnetic windings are liberally proportioned so that heat is dissipated adequately by conduction through the body and by radiation, for openings of any sort are inadmissible.

Steel of high permeability is used for the magnetic circuit, resulting in the establishment of the maximum flux density under

given conditions and enabling small poles to be used close together, tending towards a uniform holding effect over the surface. In order that no adjacent parts of the machine tool, or surrounding iron or steel objects may become magnetised by the chuck, attention is paid to reducing the stray field to a minimum, consistent with providing adequate holding power.

Although the magnetic pull perpendicular to the holding surface is considerable, the resistance to movement parallel to the surface is much less, depending on the friction between the chuck face and the work. Probably not more than 25 % of the perpendicular force can be relied upon to resist sliding. This may be sufficient to resist the force of the wheel when taking the lightest cuts on thin material on a grinding machine, but it is generally insufficient to resist the ordinary cuts applied by metal cutting tools and in heavier grinding, or when deep articles are machined. Adjustable mechanical side and end stops are therefore usually provided on magnetic chucks. The current supply is taken through an armoured or suitably protected flexible cable in the case of a chuck bolted to a fixed or moving machine table; and the controlling switch can be mounted in an accessible position on the machine frame. Where the chuck is to be used as a rotating plate, slip-rings and brushes are required to connect with the supply. The excitation of magnetic chucks is necessarily by D.C., which may be taken from lighting circuits at any voltage from 50 to 250 V. For permanent use, magnetic chucks should be excited only at the makers' specified voltage; too high a supply pressure will result in overheating and too low a value will produce a considerable loss of holding power. Under emergency conditions, a chuck may be excited at a voltage lower than its rated value, the only criterion being the adequacy of the holding force developed. On the other hand, if the supply voltage is higher than the rated value, a suitable series resistance may be inserted in circuit; the current consumption of a chuck being low, the I^2R loss in the series resistance will not usually be of any great importance.

Iron and steel articles held on a magnetic chuck will generally retain some residual magnetism after the chuck windings have been de-energised. This may result in some difficulty in removing a light or thin article from the face of the chuck; and the article, when removed, may still be magnetised to an objectionable extent. Means are therefore usually provided for demagnetising the

article after work on it has been completed. For small chucks it is usually sufficient to incorporate a reversing connection in the supply switch: the procedure on removing work from the chuck is then to throw the switch over to the reversing position for a few seconds, when the reversed magnetism will remove the majority of the residual effects. To prevent misuse of the demagnetising position, the switch is generally arranged with a spring, against the pull of which it must be held while on the reversing contacts.

A more efficient method, which must generally be employed for large articles, is to pass the work, after removal from the chuck, to and fro across a 'demagnetiser,' which is an electromagnet excited by A.C. at any convenient frequency; the effect is to alternate the magnetism rapidly and leave no appreciable residual magnetism.

There are certain restrictions in the use of magnetic chucks, apart from matters of ordinary workshop practice. The work must have a reasonably large flat surface in one plane in order to afford the necessary contact area, and, as a rule, the contact face should be a machined surface, as the presence of even the smallest air-gap seriously reduces the holding power of the chuck and, other things being equal, the force of attraction is proportional to the area of contact. For repetition work on pieces having no suitable plane face for mounting on the chuck, use can be made of specially shaped auxiliary top plates; these are machined in thickness to the varying shape of the work, and are provided with inserts of high permeability, corresponding in size and position with the pole faces of the chuck. These inserts then act as magnetic continuations of the pole pieces of the chuck itself.

Thin steel plate with the usual black finish may be held on a chuck for grinding the surface, if a suitable end stop be used, but care must be taken that the work is not temporarily sprung by the chuck, or the ground face will not be flat when the work is removed from the chuck and the 'spring' is released.

For certain classes of repetition work, such as grinding the flat surfaces of piston rings, ball-bearing races, and the like, the horizontal table of the machine may be arranged as a special magnetic chuck which is temporarily rendered magnetic when passing over a definite area beneath the grinding wheel. The work may then be placed continuously and rapidly on the non-magnetic portion of the table, to be held automatically when passing the

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wheel, and finally removed when re-entering the non-magnetic region.

The average holding force of magnetic chucks ranges from 100 to 200 lb. per sq. in. of surface. Table 175 shows the power consumption of some representative sizes of chucks :—

TABLE 175.—*Power Consumption of Typical Magnetic Chucks.*

Circular Chucks.		Rectangular Chucks.	
Dia. Overall. Ins.	Power Consump- tion. Watts.	Length × Width. Ins.	Power Consump- tion. Watts.
6	20	8 × 5	10
12	60	10 × 4	22
18	120	18 × 5½	44
24	220	27 × 12	65
30	570	34 × 9½	100
36	1 070	40 × 14	300

808. Magnetic Clutches.—In principle, magnetic clutches are plate-type friction clutches in which the engagement of the driving and driven surfaces is effected by electromagnets instead of by springs or other mechanical means. The general arrangement is for the driving shaft to carry a fixed magnet disc, in which an annular coil is sunk in a groove and supplied with current through slip-rings and brushes. A circular spring steel plate is fixed to the driven shaft, with a steel ring secured to its outer edge. When the clutch is 'disengaged' there is a small clearance between the magnet disc and the steel ring; but when the winding is energised, the steel ring is attracted towards the magnet disc against the pull of the spring plate, assuming a dished form until contact is made between the driving and driven friction surfaces. The face of the magnet disc is covered with a layer of friction lining which serves the dual purpose of providing a high coefficient of friction and forming an 'air-gap' between the magnet disc and its 'armature.' This 'air-gap' prevents sticking of the components when the current is interrupted and assures rapid disengagement under the action of the spring plate.

The advantages of such a clutch are: (1) Operation can be effected by push-button or remote control from any distance, including automatic operation by a relay, a float switch or other controlling device, enabling machines to be started and stopped automatically

according to demands; (2) no mechanism is required for operation; (3) the time lag in building up the magnetic field, together with the action of the friction surfaces themselves, provides a smooth engagement with gradual acceleration of the driven machine; (4) the two friction members are held together by mutual attraction, and there is, therefore, no unbalanced end-thrust, such as arises from mechanical methods of engagement; (5) the force between the clutch components, and therefore the power-transmitting capacity of the clutch, is determined by the pull of the magnet, which is known in advance, is constant, and is independent of centrifugal force and the wear of links, pins and the like, since these are absent; (6) the mechanical parts demanding attention are reduced to a minimum, and this fact, together with the smooth nature of the engagement, reduces the maintenance. There are also incidental advantages attending the use of a magnetic clutch, such as the elimination of mechanical controlling devices, *e.g.* unloading valves on pumps and air compressors; and the possibility of employing squirrel-cage induction motors or ordinary synchronous motors for driving when a high starting torque of the load would otherwise render the use of these machines impracticable. Further, it is possible to provide for cutting out and re-starting one of two machines or groups of machines driven from one driving machine; also, a master contact may be attached to a motor starter, which prevents the clutch being energised before the motor is connected to the line and the field excited.

When selecting a magnetic clutch for any particular drive, it should be chosen to carry, with the desired margin of safety, the maximum torque required, which will not always occur when the maximum horse-power is being transmitted; for example, maximum torque may be required when starting a driven machine containing heavy flywheels or other parts possessed of considerable inertia. The starting torque in such cases can only be determined from the known characteristics of the machine. Consideration should otherwise be given to the peak value of the horse-power to be transmitted when the load is of a fluctuating nature.

The following relationships are useful:—

Torque at maximum H.P. in lb.-ft. = $52.5 \times \text{max. H.P. per } 100 \text{ r.p.m.}$

Max. H.P. per 100 r.p.m = $0.019 \times \text{Torque in lb.-ft. at max. H.P.}$

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Direct current is, of course, required for energising magnetic clutches, and may be employed at any of the usual voltages. Standard designs are generally available for the standard range of voltages.

TABLE 176.—*Typical Single Plate Magnetic Clutches.*

(Courtesy of Igranic Electric Co., Ltd.)

Max. H. P. per 100 r.p.m.	Pull-out Torque in lb.-ft.	Max. Permissible r.p.m.	Excitation Amps.		Approx. Outside Dia. of Clutch. Inches.	Approx. wt. of Clutch. Lb.
			at 115 V.	at 230 V.		
0.7	35	3 540	0.4	0.2	7	
2.8	150	2 380	1.0	0.5	12	70
27	1 430	1 420	2.0	1.0	20	115
						350
75	3 920	1 080	3.2	1.8	28	
158	8 320	800	4.8	2.6	36	700
376	19 720	600	5.5	2.9	48	1 400
						3 300
735	38 600	480	14.0	7.3	60	
1 270	66 600	395	17.3	9.1	72	4 800
2 170	114 000	365	19.3	10.4	78	6 800
						8 200

For the transmission of particularly heavy torques with a restricted overall diameter, magnetic clutches of the multiple disc type have been constructed and employed on large locomotives with Diesel-electric drive. The driving disc containing the magnet winding is provided with a number of annular friction discs capable of small axial movement on a splined shaft. Between these driving discs are inserted other annular discs capable of small axial movement along internal splines in a rigid housing, embracing the nest of driving discs, and keyed to the driven shaft. A magnetic pressure disc, capable of small axial movement, is carried inside the housing on the driven shaft and pulled away from the friction surfaces by springs, but can be caused to press on the driven friction discs by the pull of the magnet winding. With no current passing through the winding, the pressure disc is withdrawn and there is no pressure between the two sets of friction surfaces, so that the clutch is free. On energising the magnet, the pressure disc is attracted against the force of the 'pull-off' springs and produces axial pressure between the two sets of friction discs. The multiple effect of the friction surfaces then produces a high frictional resistance and the driven shaft is rotated.

809. Magnetic Separators.—The application of an electro-magnet to a mixture of magnetic and non-magnetic materials is a useful means of separating the two substances. Many instances occur where this process is desirable, including the removal of iron and steel articles which would be detrimental or useless if allowed to remain in the mixture, and the recovery of magnetic material from natural and waste products.

Some examples of this use of the electromagnet are:—

(1) The removal of iron chippings and slag containing iron, and the like, from foundry sand, cupola cinders, foundry floor dirt; the iron separated may be remelted instead of wasted. The removal of iron turnings from brass swarf.

(2) The removal of foreign iron and steel from coal to be used in pulverised fuel plants; apart from the uselessness of such material as fuel, the delivery of bolts, nuts, etc., to the crushers and pulverisers might result in breakage and stoppage of the plant, and be likely to produce sparks, with the possibility of fires.

(3) The recovery of iron and other magnetic materials from crushed ore.

(4) The separation of iron nodules from gem-bearing gravel for the recovery of small lapidary diamonds especially.

(5) The removal of iron and steel particles from foodstuffs, glass and pottery materials, etc., where the ferrous materials might otherwise be dangerous, or detrimental to the success of the finished product.

Since the processes to which electromagnets can be usefully applied in this way are usually continuous processes, the 'magnetic separator' is generally found in connection with a conveyor, or other continuous process device. The arrangement of the separator in relation to the process is generally a mechanical matter, and the following arrangements are met with:—

(a) *Magnetic Pulley Separators.*—This type is particularly adaptable to belt conveyors, the magnetic pulley taking the place of the usual head pulley on an inclined conveyor, or that of the delivery pulley in a horizontal conveyor. Suppose, for example, that foreign or 'tramp' iron is to be removed from coal. On approaching the pulley, the iron is held against the belt, by virtue of the magnetic attraction of the pulley, over a sector wide enough to carry it past the chute into which the coal, or other non-magnetic material, is delivered. On leaving the magnetic sector, the iron is dropped into a separate chamber or discharge chute. Such pulleys are made in sizes from 12 to 36-in. diameter and in widths up to 60 ins., a range capable of dealing with up to 500 tons of coal per hour. The pulleys should be used as large in diameter as possible, in order to minimise wear and tear on the belt, and about 120 ft. per min. is a suitable belt speed.

As regards the electromagnetic features of the pulley, a number of soft steel discs are keyed to the shaft, with windings in the intervening spaces. The coils are connected in series and the terminal leads are brought out through the shaft to a pair of slip-rings by which D.C. is supplied to the windings. The coils are impregnated, and the spaces between the discs are filled solid with an insulating compound, which protects the winding from moisture and has good heat-conducting properties. By suitable proportioning of the steel and the ampere-turns in the windings, sufficient flux is provided to retain pieces of iron which have not worked down to the belt surface.

These pulleys are usually fed at voltages from 100 to 500 V and will remove pieces of iron weighing up to 50 lb. The current required is usually only a few amperes. As an alternative to using a magnetic pulley in conjunction with a belt conveyor, the pulley may comprise the active part of a separate separator. The mixture is then fed to the upper and receding side of the pulley, the non-magnetic material being thrown off by impact and centrifugal action into a hopper. Fixed exciting coils are employed, placed eccentrically inside the revolving drum, and nearest to the feeding point of the drum. The magnetic material is carried round beyond the hopper for the non-magnetic material, and is released in the neighbourhood of the lowest point, where the field is weakest, into a separate container or chute.

It has been found that coal slag is generally appreciably magnetic, whereas coal and coke are not. The difference is due to the fact that the ferriferous non-magnetic constituents in raw coal become changed, during combustion, to the magnetic state. Magnetic pulleys therefore find a useful application in the recovery of combustible matter from ash, from 30 to 50 % of the total ash being recoverable. The process has the advantage of being a 'dry' one, so that minute particles of coal or coke which would be washed away by a wet separation process are now retrieved.

(b) *Drum-Type Magnetic Separators*.—Where material is tumbled in an inclined revolving drum for grinding purposes, magnetic separation may conveniently be combined with the passage of the material through the drum. The material to be ground is fed in at the upper end of the drum and is carried up for some distance on the rising side before tumbling over to the bottom again. Electromagnets can be so arranged at the upper

end that any magnetic particles are carried round to about the top of the circular section, where they are released and fall into a chute which passes through the drum and carries them away. This type of magnetic separator is applied to ore concentration, and for gem separation, as mentioned above.

(c) *Rotating Disc-Type Magnetic Separators*.—In some cases it may be more convenient to dispense with a magnetic head pulley on a belt conveyor in favour of a conveyor of ordinary type used in conjunction with a separate magnetic device. A horizontal disc, carrying soft steel pole pieces, is then revolved above the conveying belt at a suitable place, and a fixed electromagnet is supported over the disc. The pole pieces of the disc become periodically magnetised by induction as they pass under the magnet, and they then attract the magnetic particles to be removed from the material on the belt. As the particles adhering to the disc are carried beyond the influence of the inducing magnet, they fall into a chute or container provided for their reception. This method may be applied to ore concentration, and to the removal of ferrous particles from brass machine-shop swarf.

(d) *Belt-Type Magnetic Separators*.—Fixed electromagnets combined with two belts can be readily arranged to form a magnetic separator. One arrangement is to run a second belt over the main conveying belt at a sufficient distance above it, and to place a series of electromagnets at a little distance above the upper belt. On approaching the magnetic field set up by the magnets, the magnetic articles in the material on the main belt are drawn upward and retained against the underside of the top belt as long as the top belt is moving under the series of magnets. It is purely a matter of arrangement to provide for a hopper to gather the magnetic material at the end of the magnetic area, where it drops freely from the underside of the top belt, while the non-magnetic material is carried forward on the lower belt.

An alternative arrangement is to run the 'magnetic' belt across the main belt instead of in the same direction; this cross belt may be run between the poles of a bipolar magnet.

The foregoing separators are all suited to continuous processes, and both separated materials are continuously delivered. In some instances, intermittent removal of the magnetic material will serve, and the following types are in use:—

(e) *Wet-Type Magnetic Separators*.—Where it is desired to

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remove iron from liquid or semi-liquid material, the material to be treated may be passed through a suitable non-magnetic trough in which is placed a removable tray (also non-magnetic) containing a watertight electromagnet. The ferrous material is attracted by the magnet and is retained in the tray. Periodically the tray is removed and cleared of its spoil; it is necessary, of course, for the flow of the material, and the power to the magnet, to be interrupted for this operation.

(f) *Suspension-Type Magnetic Separators*.—The separator consists essentially of a lifting magnet suitably placed above a conveyor belt carrying the material under treatment. This method is applied to the removal of scrap iron, etc., from coal and the like. A mushroom form of magnet may be used, with a horizontal coil in a soft-steel core, which gives a somewhat localised flux, and is suitable for the extraction of heavy scrap and foreign articles.

Alternatively, a bipolar magnet may be employed; this gives a wider range of flux and a greater reach over a conveyor belt and so is more suitable for the removal of smaller articles.

The supply must be cut off before the attracted articles can be dropped from the magnet; as a corollary, the conveyor will generally need to be stopped when this is done. A convenient mechanical arrangement when large articles are to be dealt with is to provide a suitable runway on which the magnet may be drawn aside from the conveyor belt before dropping the spoil. Such magnets are useful in coal preparing plants, and will retrieve material ranging from small pieces of steel wire used in blasting operations to steel chains and miners' picks.

810. Bibliography.—(See explanatory notes, § 58, Vol. 1.)

OFFICIAL REGULATIONS.

See Chap. 41 in this volume.

BRITISH STANDARD SPECIFICATIONS.

No. 302.—Round Strand Steel Wire Ropes for Cranes.

No. 327.—Derrick Cranes. *Part 1.* Power Driven. *Part 2.* Hand Operated.

No. 329.—Round Strand Steel Wire Ropes for Lifts and Hoists.

No. 357.—Travelling Jib Cranes (Contractor's Type).

No. 394.—Short Link Wrought Iron Crane Chain (excluding pitched or calibrated chain).

No. 408.—Ships' Cargo Lifting Blocks.

No. 465.—Quality of Pitched and Calibrated Wrought Iron Load Chain for Hand Operated Pulley Blocks.

No. 466.—Electric Overhead Travelling Cranes.

BOOKS.

- Electric Handling of Materials, H. H. Broughton (Benn).
 Electric Crane Construction, C. W. Hill (Griffin).
 Cranes and Hoists, Wilda (Scott, Greenwood).
 Electric Cranes and Hauling Machines, F. E. Chilton (Pitman).
 Mechanical Handling of Goods, C. H. Woodfield (Pitman).
 Electric Lift Equipment for Modern Buildings, R. Grierson (Chapman & Hall).
 Electric Elevators: Their Design, Construction, Operation and Maintenance, F. A. Annett (McGraw-Hill).
 Lifts (Brochure), Marryat & Scott, London.
 Magnets, C. R. Underhill (McGraw-Hill).

I.E.E. PAPERS.

- Electric Passenger Lifts, H. Marryat. Vol. 62, p. 325.
 New System of Control for Electrically Driven Winches and Cranes, J. Bentley. Vol. 64, p. 567.

MISCELLANEOUS.

- High Speed Lifts on Single-Phase Supply, R. E. Hopkins. *El. Rev.*, Vol. 104, p. 53.
 A Large Electric Lift. *El. Rev.*, Vol. 105, p. 293.
 Electric Power Application to Passenger and Freight Elevators, H. P. Reed. *Amer. I.E.E. Jour.*, Vol. 41, pp. 57, 152.
 Electric Cranes, C. H. Woodfield. *Jour. Junior Inst. Engineers*, Vol. 32, Pt. 2, p. 47.

NOTE (to p. 364).—For use in explosive atmospheres, where open contact wires are not permissible, cranes and runway pulley blocks (§§ 787, 790), with totally enclosed motors, may be supplied through tough-rubber sheathed trailing cables (§820). The latter hang in loops, with or without supporting 'runners,' or are kept taut by a counterweight and pulley system, or by a spring drum. Explosion-proof switchgear, plugs, etc., must, of course, be used. Official approval of the proposed installation should be sought in advance.

CHAPTER 32.

ELECTRICITY IN MINING.

811. Diversity and Extent of Uses ; Conditions.—Electric power is used to an ever-increasing extent in mining work for ventilations (§§ 824, 825), pumping (§ 826), locomotion (§ 832), haulage (§ 831), winding (§§ 827 *et seq.*), drilling (§ 836), coal-cutting (§ 834), lighting (§ 840), and such subsidiary but important applications as shot-firing (§ 838) and communications (§ 839). In addition, there are various uses confined to particular classes of mines, such as ore-crushing, screening, separating, etc. The latest available statistics (for 1931) show that about 873 000 H.P. of electric motors are used above ground in collieries in the British Isles, 961 000 H.P. below ground, or 1 834 000 H.P. total above and below ground. For metalliferous mines in the United Kingdom, the corresponding data are about 19 700 H.P. above ground, 11 900 H.P. below ground, or 31 600 H.P. in all ; while about 114 000 H.P. of electric motors are installed at quarries, including clay, sand and gravel pits. These figures are further analysed in § 842, which deals with mines and quarries other than coal mines.

New collieries are almost always driven electrically. So far as essential principles are concerned, it is immaterial whether electricity is to be used above or below ground, for one purpose or another, but in details of practice and design special points must receive attention. Thus temperatures are generally higher and ventilation worse than normal below ground ; dust, damp, and falls of rock have to be allowed for ; space is limited ; difficulties in erection are encountered ; and there is, even now, difficulty in securing adequate supervision and maintenance of underground electrical apparatus by ‘competent persons.’ Clearly all such apparatus must be of the hardest construction, and anything in the nature of delicate automatic gear is out of place.

Finally, the danger of explosions is ever present in most coal mines.

812. Advantages of Electricity in Mining; Safety; and Safety Provisions.—The general advantages of electric transmission and driving in mining work are those experienced in other industrial applications of electric power, but have here special importance owing to the scattered location of power-consuming devices in collieries and the peculiar working conditions, which make any other system of driving inefficient and more or less inflexible and inconvenient, but do not detract at all from the merits of electric driving. The chief objections urged against electrification of collieries have been the capital cost involved and the alleged dangers introduced.* The capital cost of electrical plant was being rapidly reduced, as compared to that of other plant, when our previous edition was published; since the war, the increase in price has been general, so that the proportionate reduction of pre-war days holds good. Experience has proved that electrical driving is always a sound proposition in new collieries, and generally pays for itself in collieries previously driven by steam, except perhaps in the case of winding plant (§ 827). As regards safety, the annual report of H.M. Inspector of Mines shows that fatal electrical accidents in mines are less than 1 % of the total fatal accidents, whilst the non-fatal accidents form a yet smaller percentage of the total number. Further, most of the electrical accidents which do occur are distinctly 'avoidable,' being due to neglect or contravention of rules and regulations which, if observed, would secure absolute safety; practical joking is sometimes responsible for serious accidents, and cannot be too strongly condemned wherever electrical apparatus is concerned. In 1926 there were only four fatal accidents recorded in the official Report, of which 'three ought not to have occurred if reasonable precautions had been taken'; on the other hand, in 1931, there were eight accidents involving twenty-four deaths, the comparatively serious loss of life being due to the fact that eighteen men were killed in two explosions.

The 'General Regulations as to the Installation and Use of

* See 'Some Researches on the Safe Use of Electricity in Mines,' Prof. W. M. Thornton (*Jour. I.E.E.*, Vol. 62, p. 481).

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Electricity in Mines' prescribed by the Home Office (§§ 813, 1051) are further referred to in the following paragraph, but here we may quote the one dealing with gassy mines:—*

Regulation 132. In any part of a mine in which inflammable gas, although not normally present, is likely to occur in quantity sufficient to be indicative of danger, the following additional requirements shall be observed:—

- (i) All cables, apparatus, signalling wires, and signalling instruments shall be constructed, installed, protected, worked, and maintained so that in the normal working thereof there shall be no risk of open sparking.
- (ii) All motors shall be constructed so that when any part is live all rubbing contacts (such as commutators and slip-rings) are so arranged or enclosed as to prevent open sparking.
- (iii) The pressure shall be switched off apparatus forthwith if open sparking occurs, and during the whole time that examination or adjustment disclosing parts liable to open sparking is being made. The pressure shall not be switched on again until the apparatus has been examined by the electrician or one of his duly appointed assistants, and the defect (if any) has been remedied or the adjustment made.
- (iv) Every electric lamp shall be enclosed in an airtight fitting, and the lamp-globe itself shall be hermetically sealed.
- (v) A safety lamp shall be provided and used with each motor when working, and should any indication of fire-damp appear from such safety lamp, the person appointed to work the motor shall forthwith cut off the pressure therefrom and report the matter to a fireman, examiner, or deputy or other official.

Adoption of electric driving in collieries reduces power costs by centralising generation. Extra power-using apparatus can be installed wherever required, working conditions underground are materially improved, and power losses and maintenance costs are reduced. Moisture-proof insulation and earthed sheathing on cables practically eliminate shock risk. Simple interlocks can be arranged to prevent a trailing cable plug being inserted in or withdrawn from a gate-end box whilst the switch of the latter is closed; and the plug can be so arranged that the earth-pin cannot be inserted in a live socket. By using double-wound transformers (*not* auto-transformers) wherever pressure-reduction of A.C. is required, and by earthing one terminal of the secondary of double-wound transformers, danger due to possible access of high-pressure current to the low-pressure circuit (by breakdown of insulation or otherwise) can be practically eliminated. Oil

* The minimum percentage of methane in air which can be ignited is 5.5 % by volume, while 12.2 % gives the maximum effect (160 lb. per sq. in.); the temperature of ignition is 650° C. The minimum amount of coal dust in air which forms an explosive mixture is 6 % by weight, and above 16 % is practically safe.

immersion of switchgear (§ 822) prevents ignition of explosive gases by arcing at the contacts. Enclosure and the provision of cooling baffle-plates or wide but very shallow casing-joints makes motors and other apparatus flame-proof (§§ 670, 740). Various Reports of the 'Safety in Mines Research Board' * deal instructively with flame-proof mining plant. As internal explosions *must* occur, the problem is to prevent the propagation of flame outside, which is done by either 'vented flanges' or 'plate relief' (including 'ring relief') devices.†

On haulages (§ 831) it is useful to fit the motor circuit with an overload cut-out, set to operate at such load as indicates derailed tubs or an obstruction on the track. The motor itself would generally stand a much higher load, and, but for the safety device suggested, a good deal of damage might be done to the track before the haulage driver realised that there was anything radically wrong. These few examples illustrate how electrical apparatus of all kinds lends itself readily to the provision of simple, automatic safety devices giving precisely the desired protection. Official regulations concerning the use of electricity in mines in this country are stringent, but most of the relatively few electrical accidents which occur are traceable to non-observance of the rules. Broadly speaking, all electrical equipment for use in mines should be absolutely 'fool-proof,' and it is not difficult to secure this.

The testing of electrical apparatus for flame-proofness is now undertaken by the Safety in Mines Research Board, at Buxton, which body issues certificates.

813. Regulations as to the Use of Electricity in Mines.—In Great Britain the use of electricity in mines is hedged about with an enormous mass of statutory rules issued by the Home Office (§ 1051). To some extent these rules were originally rendered necessary by the average mining engineer's ignorance of

* Papers Nos. 5, 21, 35, H.M. Stationery Office.

† An exceptionally valuable article on the whole question of flame-proof equipment and protection, including a detailed comparison of the specifications in various countries, is 'Flameproof Electrical Apparatus for Use in Mines,' by I. C. F. Statham, *Colliery Engineering*, Vol. 10, pp. 112, 158, 207, 226. In the Reports of the Safety in Mines Research Board (H.M. Stationery Office), Paper No. 5 deals with flange protection, No. 21 with perforated plate protection, and No. 35 with ring relief protection.

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electrical matters and his tendency to underestimate the consequences of carelessness in installing and operating electrical equipment. Conditions are, however, so special in mines that the safeguard of stringent official rules could hardly have been omitted under any circumstances, and, on the whole, the British regulations have been found conducive to safe working without impeding progress in utilising electricity in mines. The regulations have been amended from time to time in accordance with widening experience, and no useful purpose would be served by dealing with them at length in these pages; though many are quoted *verbatim* in this chapter, with relevant extracts from the official memorandum on them.* The complete set of regulations is obtainable through any bookseller at nominal cost; a selection of them may be found in Glover's *Electric Mining Regulations and Data*.

POWER SUPPLY IN MINES.

814. A.C. versus D.C.; Load- and Power-Factor, etc.—As in other industrial power applications, high-tension 3-phase supply is the accepted standard for transmission to or generation in colliery power houses. This system undoubtedly offers a maximum of efficiency and economy in serving miscellaneous scattered power loads, some of which are very large. The turbo-alternator is a cheaper, more efficient, and more convenient machine than the turbo-dynamo; and A.C. can be transmitted at high pressure and transformed to lower pressures without use of rotating machinery. D.C., on the other hand, involves simpler circuits and switchgear, and D.C. motors have especial advantage in respect of speed control and high starting torque. Squirrel-cage induction motors are the acme of simplicity and strength, but, for all except the lowest horse-powers, it is necessary to use slip-ring motors, and these offer no advantage over commutator motors in respect of low explosion risk. By use of liquid or other starting resistances in the rotor circuit (§§ 723, 739) it is possible to develop sufficient starting torque in the induction motor for most mining purposes, and, as stated above, the balance of opinion is undoubtedly in favour of 3-phase A.C. working, with auxiliary D.C. supply from rotary converters (§ 408 *et seq.*) for special purposes.

* Reproduced by the permission of the Controller of H.M. Stationery Office.

Even with the best transmission conditions that can be maintained underground, the power losses and the investment of copper increase formidably as a mine becomes older and the transmission lines for carrying low-voltage current are lengthened. In order to remedy these conditions the underground converter station has been introduced into the mine power system. A great decrease, both in transmission line losses and the amount of copper required, is effected by transmitting power as A.C. of high voltage to substations near the centres of power consumption and there converting it into low-voltage D.C., to be transmitted over short distances to the mining machines and locomotives. The approved practice is to carry the high-tension A.C. over surface transmission lines to points directly above the substations and thence by cables through bore-holes from the surface to the stations.* At these points motor-generator sets or transformer and rotary converter equipment alter the high potential A.C. to 250-volt D.C. The motor-generator set has been commonly used because of the difficulties formerly experienced in the operation of 60-cycle synchronous converters. The recent perfection of the latter type of machine by the use of interpoles has made this type of converting equipment adaptable to mining use, and some installations have been made. These have the advantages over the motor-generator set of lower cost, higher efficiency, and the possibility of adjusting the power factor, which cannot be accomplished with the induction motor-generator set. The disadvantages in the use of the rotary converter are that transformers are required and more care is necessary in starting the synchronous rotary, because it must be started, brought up to speed, and synchronised with the power source before it may be connected with the power line.

Some have advocated the elimination of the converter equipment and D.C. commutation troubles by the use of A.C. equipment for all mining work. There are, however, the compensating disadvantages of the lack of flexibility in operation of A.C. motors, low starting torque, the greater amount of copper required for power transmission at a given low voltage, and the low power factor when induction motors are used. Power factors as low as 80 % have been reported in the case of A.C. mining-machine circuits, and a P.F. of 60 % for the entire mine is considered average practice.

(Arthur J. Hoskin and Thomas Fraser in Bulletin 144 of the University of Illinois.)

Where private generating plant is installed (§ 816), the generators should be capable of supplying their rated kilowatts of true power output at 0.75 P.F. (§ 155 *et seq.*), and the demand varies so greatly on different sections of a widespread system that automatic voltage regulation by Tirrill regulators (§ 147) or equivalent means is very desirable. Transmission may be at 3 000, 11 000, 20 000 V, or higher pressure, according to the amount of power to be transmitted and the distance of transmission.

* This method is rarely, if ever, applicable in the United Kingdom, owing partly to wayleave difficulties and partly to the prohibitive cost of bore-holes where deep seams are concerned. The method is, however, economical where seams are relatively near the surface, as is generally the case in the U.S.A.

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Regulation 126 prescribes that: (a) Where electricity is distributed at a pressure higher than 650 V (i) it shall not be used without transformation to medium or low pressure except in fixed machines in which the high or extra-high pressure parts are stationary; and (ii) motors under 20 H.P. shall be supplied with current through a transformer stepping down to medium or low pressure.

(b) Where energy is transformed, suitable provision shall be made to guard against danger by reason of the lower pressure apparatus becoming accidentally charged above its normal pressure by leakage from or contact with the higher pressure apparatus.

Large motors may be operated at 2 000 or 3 000 V, 3-phase; motors of less than 50 H.P. may be supplied at 250 to 600 V, 3-phase; and lighting supply may be at 100 or 110 V, single-phase or D.C. The possibility of present or future co-operation with existing power supply companies must be taken into consideration when selecting the frequency at which A.C. is to be generated in private plant; for under the Electricity (Supply) Act, 1926, the Electricity Commissioners have power to enforce standardisation. Apart from this consideration, the choice usually lies between the British Standard frequency of 50 cycles (adopted by the Commissioners generally) and the subsidiary standard of 25 cycles (§ 135 (5), Vol. 1). Machinery and transformers for 50-cycle current are lighter and cheaper than for 25 cycles, but the P.F. is better on the lower frequency. The net advantage, however, is in favour of standard 50-cycle supply, since this permits higher speed in the turbo-generators (3 000 r.p.m. as against 1 500 r.p.m.), and gives a wider range of speeds in the motors supplied. An excellent review of the conditions of generation and distribution in a large colliery scheme is to be found in a paper by C. P. Sparks (*Journal I.E.E.*, Vol. 53, pp. 389 *et seq.*) dealing chiefly with the electrical features of the Powell Duffryn collieries (South Wales), where about four million tons of coal are raised per annum, and examples are to be found of most forms of electric drive. In the Aberdare and Rhymney valleys there are nearly 45 000 motors connected for colliery purposes, these being supplied by 24 000 kW of generating plant (0·54 kW per H.P. of motor installed), furnishing 50 000 000 kWh per annum (1 120 kWh per annum per motor H.P. installed). The diversity factor (= Total H.P. connected ÷ Maximum demand (§ 263 *et seq.*)) is about 3; the power factor of the Aberdare valley load is 0·7 to 0·85, whilst that of the Rhymney valley load is 0·7 to 0·8; and the load factor of both valleys combined is as high as

55 to 60 %/. The load factor of the Aberaman colliery alone is 47 %/. These data may be taken as a useful guide to the results obtainable in any large colliery, when fairly completely electrified.

815. The High-Pressure Constant-Current System in Mines.—The possibilities of high-pressure D.C. working on the Thury system (§ 317) in mines were discussed fully by S. F. Walker a few years ago (*Journal I.E.E.*, Vol. 51, pp. 443 *et seq.*), but no practical application of the system has yet been made in this field. The high-pressure constant-current system is primarily suitable for transmission purposes (§ 317), whereas colliery conditions are chiefly those of distribution. Short-circuiting switches provide against interruption of supply in the event of one motor in a series circuit breaking down, but a break in a cable (due to a fall or other mishap) interrupts service on the whole circuit of which that cable forms part. Since a full-sized cable must be run throughout a series circuit, the system is extravagant of copper when supplying outlying motors; but perhaps the most serious difficulty of all, in applying this system to mining work, is that of insulating the motor from the machine it drives and of using foundations of concrete or glass insulators and bitumen (or an equivalent construction). Though the system would introduce considerable advantages in some directions, its disadvantages seem to be more weighty, if not practically insuperable.

Mr. H. M. Sayers has revived interest in this system* by suggesting its use for transmission in rural and 'thin' areas, with parallel distribution; and possibly this may be applicable in mines

816. Private Generation versus Purchase of Energy; Prime Movers for Colliery Service.—The subject-matter of this paragraph will also be found in § 185 (Vol. 1), where the question is discussed without special reference to mines. During recent years, increase in the size of generating units both for public and private plants has been rapid, and what follows may be taken as applicable generally. But a colliery installation is in a class by itself, since its power demand may equal that of a medium-sized town; †

* *El. Rev.*, January 13, 1928, p. 48.

† At the Fuel Conference, 1928, it was stated by Prof. D. Hay that over a million kW of plant is installed in British collieries, with overall costs sometimes as low as 0.25 d. per kWh and very low transmission losses. In some areas these stations generate more units per annum than the local power companies.

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and it is recognised in the schemes that have been formulated by the Central Electricity Board that a modern group-colliery plant may be large enough and economical enough to work in co-operation with, or itself to be, a 'selected station' (§ 1041 (vii)). Mr. J. Kennedy* has remarked :—

'At the present prices of machinery and coal the Board would be able to put turbine-units of, say, 25 000 kW into their stations, and produce electricity at prices, respectively, of £2 5s. per kW and 0.125d. per unit generated, with coal at about 15s. per ton.† At 80 % load-factor that was equivalent to 0.3d. per unit, including interest. It was therefore obvious that collieries would have to produce electricity at about that figure if they were going to be able to supply the Central Electricity Board.'

It is a mistake to assume that power can always be generated at the pit mouth more cheaply than it can be purchased from a power company. Even the poorest grades of fuel have involved an appreciable cost per ton by the time they reach the pit mouth, and they have certainly had an enhanced market value, since machine stokers and pulverising plant have been so much improved that almost any fuel can be burned efficiently under steam boilers. The problem of deciding on the best arrangements for power supply in collieries is thus not at all simple; full consideration of individual circumstances is essential, and (subject to approval by the Electricity Commissioners) the alternatives to be borne in mind are: (i) Generation in private plant serving the colliery alone; (ii) generation in private plant serving a group of collieries‡ or operating in parallel with a power company's plant, which is drawn upon during periods of heavy load, and to which assistance is given when the colliery demand is low; (iii) erection of a plant to supply all the industrial power requirements of the neighbourhood, including the colliery; (iv) purchase of all energy required from an existing power company. Selection from amongst these alternatives is almost entirely a commercial problem. The extent and nature of the colliery load must be estimated, and the cost of private generation compared with that of purchasing energy, taking into account present and future needs, total demand, load

* *Progs. Inst. C.E.*, Vol. 223, p. 225.

† Coal at the pit's mouth may cost as little as 8s. per ton.

‡ The grouping of collieries in the matter of power production is discussed in 'The Economics of Power Production and Utilisation at Collieries,' by Professor D. Hay (*Progs. Inst. C.E.*, Vol. 223, p. 194).

factor, fuel costs at the colliery, the possibility of by-product recovery or exhaust-steam utilisation, and so on.

One large group of collieries generating their own power recently branched out on new lines. The blast-furnace gas from the associated ironworks is used to drive gas engines, directly coupled to alternators, where hitherto the gas has been burnt under boilers to generate steam for turbines. The overall efficiency is expected to be of the order of 25 %.*

Tenders for the supply of so many units (kWh) per annum at such and such power and load factors can be obtained at once from existing power stations. In considering the possibilities of private plant, the three main alternatives are: (i) Use of electricity for all purposes, energy being obtained from generators driven by high-pressure turbines; (ii) retention of existing steam engines driving winding gear and compressors, exhaust steam from these engines being used in exhaust- or mixed-pressure turbines to produce electrical energy for all other drives; (iii) gas engines utilising coke-oven or blast-furnace gas, and driving alternators. A new colliery in the supply area of a large power company will generally find it best to purchase electrical energy for all purposes from that company. If no power company is already operating in the district (an increasingly unlikely contingency as the projects of the Central Electricity Board materialise), the colliery might seek general supply powers for itself, or at least endeavour to secure one power station to supply all the pits in the district; in such a case the kW-capacity of the station plant would generally be about one-third the total kW-rating of the motors served. Existing collieries with good steam-driven winding gear may find it best to retain the latter, adding mixed-pressure turbines to utilise exhaust steam to the best advantage (*but see* § 817). When a colliery has a large surplus of coke-oven gas there are many advantages in co-operation with a public supply authority, *i.e.* the running of a surplus heat generating station, feeding into the authority's mains when excess energy is available.

It is interesting to note that portable battery trucks are in use, in place of power direct from the generators, in some mines in the United States, where they are used for operating coal-cutters in gassy mines, with the approval of the Department of the Interior.

* *Journal Inst. E.E.*, Vol. 65, p. 352.

817. Utilising Exhaust Steam ; Steam Accumulators.—

The utilisation of 'low-grade' heat and of steam accumulators has already been dealt with in Vol. 1 (§§ 176 and 177), and where this is possible private generating plant may, in point of economy, have an advantage over the purchase of energy even from a modern super-station. The installation of low-pressure or mixed-pressure turbines is generally sound practice wherever large, high-efficiency reciprocating engines are already in use ; though the capital cost of the low-pressure turbine and steam accumulator equipment be higher than that of a live steam turbo-set of equal capacity, the former generally shows considerable net annual saving and often provides for all auxiliary power requirements, and even furnishes a surplus of energy for sale, without increasing steam consumption. The amount of exhaust steam available for utilisation varies widely in different plants, but is easily estimated in each particular case. From the winding and compressor engines of a pit there may be available 20, 30, or 40 tons per hour of exhaust steam ; but since winding is intermittent, the maximum rate of flow may be perhaps one ton a minute for short periods, followed by other short periods during which little or no exhaust steam becomes available. The capacity of the low-pressure turbine must be based on the average supply of exhaust steam available, and it is advisable, in such cases, to use mixed-pressure turbines in preference to exhaust turbines, since the live steam supply can then be increased and utilised efficiently in the turbine, when the exhaust steam supply is inadequate, without throttling live steam wastefully down to exhaust pressure to make good the deficiency. When using both live and exhaust steam, the consumption of each depends on the amount of exhaust steam available ; naturally, live steam should only be used to cover insufficiency in the supply of exhaust steam. When operating entirely on live steam, a mixed-pressure turbine becomes practically a high-pressure turbine, and consumes, say 14 to 15 lb. steam per kWh (§ 173) in the sizes of machine generally used in this connection, say 1 500 to 3 000 kW. When operating entirely on exhaust steam, the consumption may be 30 to 35 lb. per kWh, up to 40 lb. per kWh in the case of small sets or where the vacuum is poor. For satisfactory results, an ample supply of condensing water is particularly important where low-pressure turbines are employed to utilise steam at or near atmospheric pressure (§ 175).

PLANT IN MINES.

818. Motors for Mining Work.—Motors and their control have already been treated in Chapters 28 and 29; here we confine ourselves to their special applications in mines. Open-type motors are suitable only for use in the power house, and a few other specially favourable applications in colliery installations. Protected motors (§ 870) have little wider scope, since they are unsuitable for use in dusty situations or where sparking would involve risk of explosion. In screening-houses and similar situations, pipe-ventilated motors are convenient (if air supply is readily available), since they permit dust to be excluded from the windings without involving the heavier and more costly construction necessitated by complete enclosure. Main haulage motors and other large machines used in well-ventilated situations may be used without total enclosure, but it is generally necessary to employ totally enclosed motors underground. In 'fiery' mines no point of possible sparking must be left unenclosed (§ 812). It may be sufficient to enclose the slip-rings of haulage and other motors in well-ventilated situations, but all the machines used in-by must be 'explosion-proof.' This means a good deal more than is generally implied by the term 'total enclosure' (§ 670); the latter is only a relative term where motors are concerned. It is impossible to prevent explosive gases being drawn into the interior of a motor casing by the 'breathing' action resulting from alternate heating and cooling of the machine (§ 812). One must therefore reckon that explosions will inevitably occur within the motor casing, which must be strong enough to resist the shock, and so constructed as to prevent the explosion from spreading. The most explosive mixture of air and methane (§ 812 footnote) (about 12 %) develops a maximum pressure of about 160 lb. per sq. in., hence the motor casing and cover bolts should be designed to withstand at least this pressure. In addition, the casing must be strong enough to resist hard usage in the way of chance blows or falls, etc. The cover joints should be wide, and consist of metal to metal (*without* packing). A joint of this type is not gas-tight, but cools escaping products of an internal explosion to well below the minimum temperature required to ignite inflammable gases outside the casing; the principal employed is precisely that of the Davy safety lamp. Wherever slip-

rings or commutators are employed, there is bound to occur some sparking, and the danger point must be enclosed before the machine can be used safely in a gassy mine.*

The permissible temperature to which the motor windings may rise depends ultimately on what the dielectric can stand; hence, with the high initial temperatures found in deep shafts, a lower rise must be specified; a rise of 60° F. will be on the safe side. This necessarily means a larger motor, and where space limitations are very severe (as in coal cutters), high temperature rise must be admitted, and provided for, in the construction of the machine. Intermittently rated motors take up less room than their continuously rated counterparts (§§ 136, 670), and, fortunately, most motors for use underground (with the notable exception of pump motors) may be rated for intermittent service.

For reasons already explained (§ 814) A.C. supply is generally preferred to D.C. in colliery service. Squirrel-cage motors (§ 682) with star-delta or auto-transformer starting gear (§ 724) in all but the smallest sizes may be used wherever high starting torque is not required—or rather, wherever the starting current and P.F. involved can be tolerated; starting currents and power factors which would not be permissible in a general supply scheme may have no appreciable effect, or may be accepted as a matter of expediency in an industrial power scheme. Where high starting torque is required, and in practically all cases where more than 10 or 20 H.P. is concerned, slip-ring motors are employed, with liquid resistance starters and controllers (§ 822). Where D.C. motors are used, the series type (§ 676) may be applied to pumps, haulages, and other loads where high starting torque is required, and arrangements are such that the motor cannot ‘race.’ Shunt-wound motors (§ 675) are useful in connection with machines started and stopped through a clutch or having to run light at times without racing. Compound-wound motors (§ 677) combine the high starting torque and drooping speed-load characteristic of the series motor with the freedom of the shunt motor from racing on light loads.

819. Electric Cables† for Mines.—Although the general considerations regarding cables and transmission in Chapters 13

* See ‘Flameproof Electrical Apparatus for Use in Mines,’ Prof. I. C. F. Statham, *Colliery Engineering*, Vol. 10, pp. 112, 153, 207, 226.

† For Cables in general, see Chapter 13 (Vol. 1).

and 14 apply to mines, the conditions are special in several respects. Mining loads differ from others in their large proportion of intermittent work; the ambient temperature in the workings is often high; owing to the nature of the ground, both wet and corrosive, the overall size of the cables may be different from the normal, so that the escape of internal heat (§ 291) is modified; and the permissible drop in, and variation of, pressure is less restricted than where circumscribed by the requirements of a lighting load. The selection of the appropriate type and size of cable is difficult, owing to lack of data and the conflicting figures published, so that empirical values are often used and result, on the one hand, in extravagance and, on the other, in inadequacy. In a paper on 'Electrical Transmission and Distribution at Collieries,'* Messrs. W. T. Anderson and H. M. Crellin bring together much useful information on the subject.

Between the generating station or substation and the pithead, armoured cables may be laid directly in the soil, or, if the ground contain corrosive materials, in troughs filled with pitch or bitumen. Unfortunately, subsidences are frequent and considerable in the neighbourhood of collieries, so that cables laid in the ground should be given plenty of 'slack,' and are even then liable to injury. Overhead lines are not subject to this risk, but the use of bare overhead conductors round about the pithead is not very desirable from the safety standpoint. As a compromise, insulated cables may be carried overhead by slings from a catenary wire, or laid in a covered trough (with filling material) mounted on short posts. Where A.C. supply is employed, current may be taken down the pit-shaft at high pressure, practically any standard type of high-tension cable (§§ 287 to 289) being suitable, so long as it is supported so as to limit the stress placed upon it by its own weight. Double-wire armouring is generally used for mechanical protection and to take the pull off the insulation. Either paper insulation with lead covering or vulcanised bitumen or vulcanised indiarubber may be used as dielectric, the latter materials being less liable to electrolytic damage and being non-hygroscopic, but mechanically weaker than the paper-lead construction. Paper-insulated cables must be ordered specially for shaft

* *The Mining Electrical Engineer*, March and August, 1926; reprinted by Messrs. Glover & Co. as 'A Guide to Cable Sizes.'

service; otherwise there is a risk that the impregnating oil used will drain to the bottom of the cable and burst the lead sheathing. Bitumen softens at about 100° F., and this somewhat limits its sphere of utility, owing to the risk of the core becoming decentralised. In certain circumstances it may give rise to gas. Solid-filled, vulcanised bitumen cables are, however, in high favour for moderate pressures (C. J. Beaver, *Electrician*, Vol. 71, pp. 617 *et seq.*; W. T. Anderson and H. M. Crellin, *The Mining Electrical Engineer*, March, 1926). Aluminium may be considered as an alternative to copper in the conductors of shaft cables; a bare aluminium conductor is equivalent to steel, and considerably superior to copper in respect of supporting its own weight, but allowance must be made for the extra weight of insulation on the larger aluminium cores required for equal conductivity. Since joints are seldom required in shaft cables the relative difficulty of jointing aluminium conductors does not come in question. Suspension by a single top clamp is permissible only in shallow shafts. Long wooden cleats at intervals give the best combination of effective support with small risk of direct mechanical or thermomechanical injury; the cleats may be attached to carrier chains or ropes, they may rest on the cross-buntions or girders in the shaft, or they may be secured to the wall of the shaft by rag-bolts. Alternatively, shaft cables may be fixed in a continuous casing, gripping them throughout their length, but this is apt to cause excessive temperature rise and expansion stresses. Flexibility in suspension is desirable, and, in the case of lead-sheathed cables, the sheathing must be supported so that it does not wrinkle downwards and tear at the top under its own weight.

The cleat should be in principle a friction clutch, not a pinching grip. The grooves that take the cable should therefore be cut to the exact diameter of the cable; the $\frac{1}{8}$ in. taken out by the saw when cutting them into two halves will ensure that they grip properly. The bolts that hold the two halves together should not be larger than $\frac{5}{8}$ in. or $\frac{3}{4}$ in., which will give ample grip. Each individual cleat should be about 2 ft. 6 in. long, and be chamfered off at the top to prevent the lodgment of small dirt, slime, etc.; an umbrella of sheet-iron to keep off water and deflect falling stones, etc., may also be provided. The class of wood will depend on the pit-water, and, provided it is hard, may be best left to the judgment of those who know the pit. The distance apart will depend on the weight of the cable. A cleat so dimensioned should not be loaded permanently with more than 7 cwt., which gives a distance of 25 yards to 35 yards for heavy cables. [*Glover & Co.*]

Where it is essential that current supply shall be uninterrupted, as in pumping operations, where flooding of the workings

might result from a cessation, duplicate cables are generally employed. These should be placed on opposite sides of the shaft, or, better, run in separate shafts. It is not desirable to place cables in upcast shafts, since the air therein is hot and foul.

For distribution purposes underground, paper-insulated, lead-sheathed and armoured cables are quite satisfactory so long as moisture is excluded carefully at all joints. Special joint boxes have been evolved for mining service; the filling compound must have high insulation resistance, and must be poured at the correct temperature to ensure its filling the box completely. Water in mines is frequently corrosive in nature, and bitumen-sheathed cables are often employed, since bitumen is unaffected by many materials which corrode lead. Paper-lead cables are very 'cool-running,' strong mechanically, and can be used in relatively hot situations so long as a suitable impregnating oil has been used. The chief disadvantages of bitumen are its brittleness when cold and its softness when hot, but the construction of bitumen cables has been much improved during recent years. Rubber cables are too costly for use except in making short connections.

Permanent distributing cables underground should be placed where they will be subject to minimum risk of damage by falls or blows (*e.g.* beneath girders, etc.). They should be suspended flexibly by slings which, in the event of falls, will break before the cable itself is strained unduly; this may be secured by providing a weak link in each sling. If slings be too far apart or subject to vibration, the cable sheathing is liable to be injured. Armouring, properly bonded and earthed, guards against shock accidents and provides an earthing path for apparatus at the far end. On the other hand, armouring may be forced through the insulation and cause a short-circuit when an unarmoured cable would survive the same rock-fall by yielding to it. The mechanical and electrical protection afforded by armouring may be provided on existing unarmoured cables by using split conduit bolted round the cable *in situ*, and suspended by chains or otherwise. Under the conditions usually existing in mines, multicore armoured cables are called for under Regulation 129. This regulation demands that, unless so placed or otherwise safeguarded as to prevent danger, all cables, other than flexible cables for portable apparatus and signal and telephone wires, shall comply with the following requirements :—

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(a) They shall be covered with insulating material (except that the outer conductor of a concentric system may be bare). The lead sheath of lead-sheathed cables and the iron or steel armouring of armoured cables shall be of not less thickness respectively than is recommended by the Engineering Standards Committee (*i.e.* the B.S.I.).

(b) They shall be efficiently protected from mechanical damage, and supported at sufficiently frequent intervals and in such a manner as adequately to prevent danger and damage to the cables.

(c) Concentric cables, or two-core or multi-core cables protected by a metallic covering, or single-core cables protected by a metallic covering which shall contain all the conductors of the circuit, shall be used (i) where the pressure exceeds low pressure; (ii) where the roadway conveying the cables is also used for mechanical haulage; and (iii) where there may be risk of igniting gas, coal dust, or other inflammable material.

Provided that if the medium-pressure D.C. system is used (i) two single-core cables protected by metallic coverings may be used for any circuit if the said metallic coverings are bonded together by earth conductors so placed that the distance between any two consecutive bonds is not greater than 100 ft., measured along either cable; and (ii) two single-core cables covered with insulating material efficiently protected otherwise than by a metallic covering may be used in gate roads (except in gate roads which are also used for mechanical haulage, or where there may be risk of igniting gas, coal dust, or other inflammable material) for the purpose of supplying portable apparatus.

(d) Cables unprotected by metallic covering shall be properly secured by some non-conducting and readily breakable material to efficient insulators.

(e) The metallic covering of every cable shall be (i) electrically continuous throughout; (ii) earthed, if it is required by Regn. 125 (a) (§ 821, herein) to be earthed, by a connection to the earthing system of not less conductivity than the same length of the said metallic covering; (iii) efficiently protected against corrosion where necessary; (iv) of a conductivity at all parts and at all joints at least equal to 50 % of the conductivity of the largest conductor enclosed by the said metallic covering; and (v) where there may be risk of igniting gas, coal dust, or other inflammable material, so constructed as to prevent as far as is practicable any fault or leakage of current from the live conductors from causing open sparking.

Provided that where two single-core cables protected by metallic coverings bonded together in accordance with paragraph (c) of this Regulation are used for a circuit, the conductivity of each of the said metallic coverings at all parts and at all joints shall be at least equal to 25 % of the conductivity of the conductor enclosed thereby.

(f) Cables and conductors, where joined up to motors, transformers, switch-gear, and other apparatus, shall be installed so that (i) they are mechanically protected by securely attaching the metallic covering (if any) to the apparatus; and (ii) the insulating material at each cable end is efficiently sealed so as to prevent the diminution of its insulating properties. Where necessary to prevent abrasion or to secure gas-tightness there shall be properly constructed bushes.

Of the protective systems in general use, the Ferranti-Field system (§ 352, Vol. 1) and the Ferranti-Waters system have been developed for use in mining circuits; and the various split-conductor systems (§ 359, Vol. 1) can also be used. On dead-end

feeders, which form a majority in underground working, leakage protection of the core-balanced transformer type (§ 359, Vol. 1) is frequently used. For transmission between collieries both Merz-Price (pilot) and Merz-Hunter (split-conductor) protection is used. Leakage protection, to supplement overload protection, is widely used upon 3-phase installations, and time lags, usually with an inverse time / current characteristic, are very generally employed with overload trip-coils.*

820. Trailing Cables.—‘Trailing’ cables, for connecting portable machines to the permanent distributing cables, are inevitably exposed to rough handling and consequent mechanical damage, as well as to corrosive action, acid or alkaline, from the floor on which they trail or are dragged; ordinary methods of protection by armouring are inadequate and sometimes even dangerous. For this class of work, cables should be fireproof and as nearly indestructible as possible; asbestos and similar coverings secure the former property, whilst interlaced braidings of leather, whipcord, rope, and the like ensure the latter. Trailing cables should have flexible cores (§ 284) and an earthing core with at least 50 % of the carrying capacity of one main conductor; rubber insulation is generally employed, and sheathed with vulcanised bitumen or cab-tyre sheathing (§§ 283, 287). On the efficient construction and maintenance of trailing cables the safety of the operatives largely hangs, and improvements are constantly evolved. Obviously any additional protection that increases the overall diameter also reduces the essential flexibility, as in the case of the ‘cracore’ system. A flexible copper braid of ‘ferflex’ braiding is often used underneath the outer rubber sheath, and earthed with the earth-core, but the ‘ferflex’ is liable to break in course of time and may give a false sense of security. Repairs, which must in all cases be carried out at the surface (*vide* Reg. 131 (i) below), require extra care; all joints must be vulcanised, and, in the case of ‘ferflex,’ soldering is replaced by using an overlapping mat of braided copper, which does not render the joint brittle.†

Plugs for temporary connections should make no contact till the plug and socket shells have met to form a totally enclosed space round the contacts, and then the earth contact should be made first. Regulation 130 prescribes that—

* *Jour. I.E.E.*, Vol. 373, p. 125.

† *El. Review*, Nov. 4, 1927, p. 767.

(a) Flexible cables for portable apparatus shall be two-core or multi-core and covered with insulating material which shall be efficiently protected from mechanical damage. If a flexible metallic covering be used either as the outer conductor of a concentric system or as a means of protection from mechanical damage the same shall not alone be used to form an earth conductor for the portable apparatus.

(b) Every flexible cable for portable apparatus shall be connected to the system and to the portable apparatus itself by a properly constructed connector.

(c) At every point where flexible cables are joined to main cables a switch capable of entirely cutting off the pressure from the flexible cables shall be provided.

(d) No lampholder shall be in metallic connection with the guard or other metal-work of a portable lamp.

Regulation 131 (i) requires that—

Every flexible cable shall be examined periodically (if used with a portable machine, at least once in each shift by the person authorised to work the machine), and if found damaged or defective it shall forthwith be replaced by a spare cable in good and substantial repair. Such damaged or defective cable shall not be further used underground until after it has been sent to the surface and there properly repaired.

In his Report for 1926* the Electrical Inspector of Mines calls attention to a modification of the usual type of trailing cable.

‘While the true flexible cable, with a cab-tyre or tough rubber sheath, still holds the field and indeed is not likely to be improved upon for use with coal-cutting machines and for portable drills, where great flexibility is necessary, there is scope for another type of cable for other classes of coal-face machinery, such as conveyors.

‘With such machines, which are not locomotive, but which have to be moved forward either daily or at longer intervals, a cable having relatively less flexibility suffices, provided it is sufficiently pliable to allow the surplus, which is necessary to permit the regular advance of the machines, to be coiled down, or otherwise conveniently stowed out of the way of the traffic.

‘Such *pliable cables* are actually in use at several collieries . . . and have given complete satisfaction. Internally these cables are exactly like an ordinary trailing cable, but in place of the outer layer of tough rubber there is a sheathing of stranded galvanised steel wires which serves as the earthing conductor for the apparatus, having the requisite conductivity for that purpose, and also provides a strong barrier of earthed

* H.M. Stationery Office.

metal between the live cores of the cable and the persons who have to handle it.

‘Outside the stranded armouring there is a braiding of hard cord to check any tendency to bird-caging of the armour. . . . Plug connectors at each end of the cable are unnecessary. . . . Instead, the cable is made off to cable dividing boxes, in which it can be properly sealed, and these boxes are bolted to the gate-end or other terminal fitting of the permanent cable at one end and to the machine at the other end. The hazard inseparable from the use of detachable plugs is thus eliminated, without the expense and complication of automatic electrical interlocks between machine and gate-end switch.

‘For equal duty this cable is little, if any, larger than a plain cab-tyre sheathed cable.’

821. Earthing in Mines.—The subject of earthing has already been considered in connection with public supply undertakings (§ 354); and in regard to traction *see* § 903. In mining work, owing to the confined space and the impossibility of keeping insulation perfect under all conditions, it is imperative to protect workmen from shock; the majority of accidents in British mines have been due to inefficient earthing or to no earthing at all. Regulation 124 (c) prescribes that—

Every part of a system shall be kept efficiently insulated from earth, except that (i) the neutral point of a polyphase system may be earthed at one point only; (ii) the mid-voltage point of any system, other than a concentric system, may be earthed at one point only; and (iii) the outer conductor of a concentric system shall be earthed. Where any point of a system is earthed it shall be earthed by connection to an earthing system at the surface of the mine.

It is generally agreed that the neutral point of polyphase systems should always be earthed in mining practice; the most tempting claim made for the ‘unearthed neutral’ is that it permits working to be continued with one fault on the system. This is most dangerous in mining work, and should be regarded as the very reason why the unearthed neutral system may not be used. By using an earthed neutral and selective devices interrupting supply only in faulty sections, interruption occurs only when and where it is essential to safety. Regulation 124 (d) and Memorandum * thereupon specify that—

* See first footnote to § 813 *supra*.

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Efficient means shall be provided for indicating any defect in the insulation of a system.

(*Memorandum.*)—The primary object of this Regulation is to ensure that defects of insulation shall not escape notice at any stage of their development. It must not be confused with the provision of a leakage protective device, such as that based upon the principle of core-balance for polyphase systems. A distinction must be recognised between insulated and earthed systems. For insulated systems a voltmeter, or milliammeter, connected between each live pole and earth will give the required indication, provided the insulation resistance of the sound pole or poles is high relatively to that of the defective pole.

On high-pressure systems the capacity current may mask any small leakage, because the floating neutral point will approximate to earth potential. Ordinary incandescent lamps may be utilised on low-pressure or medium-pressure systems, but an instrument is preferable. For earthed systems, a low-reading ammeter may be connected between the earthed point and the earthing system, if suitably protected against overload by a quick-acting switch to short-circuit the ammeter. Such an instrument for A.C. systems will usually be connected to the secondary winding of a suitable current transformer.

Obviously on a concentric system with bare earthed outer, no indication can be obtained of the state of the insulation while current is being used. It is particularly important, therefore, that frequent tests shall be made with an ohmmeter or by equivalent means.

As an aid to maintaining a high standard of insulation, a continuous indication of leakage is indispensable, such as that provided by a suitable chart-recording instrument. If properly utilised, such a record will be found invaluable in anticipating and thereby avoiding serious defects of insulation which would otherwise result in inconvenient interruption of the service. A continuous record must obviously be of much greater value than occasional inspection of an instrument dial, for many faults are intermittent and transient in their incipient stages. Whatever the means provided it should be checked periodically to ensure that it is in effective working order. It is generally assumed that for a 3-phase system with earthed neutral the ordinary overload protection suffices for the purpose of this Regulation also, but a little consideration will show that such means cannot be relied upon to indicate any defect in the insulation of the system. A sensitive leakage protective device, however, affords a much closer approximation to the requirements of this Regulation.

Indicating the state of insulation of cables by connecting two lamps or groups of lamps in series with an earth connection between them at the middle point (§ 1031) is, at best, a rough method, and if both poles are faulty there may be no indication of the fact. Leakage from a system of mine-cables should not exceed one-thousandth of the maximum current supplied.

Regulation 125 relates to the extent to which earth connections are to be provided in mines, and specifies that—

(a) All metallic sheaths, coverings, handles, joint-boxes, switchgear frames, instrument covers, switch and fuse covers and boxes, and all lampholders, unless efficiently protected by an earthed or insulated covering made of fire-resisting material, and the frames and bedplates of generators, transformers, and motors

(including portable motors) shall be earthed by connection to an earthing system at the surface of the mine.

(b) Where the cables are provided with a metallic covering constructed and installed in accordance with Regln. 129 (e) (§ 819 herein), such metallic covering may be used as a means of connection to the earthing system. All the conductors of an earthing system shall have a conductivity at all parts and at all joints at least equal to 50 % of that of the largest conductor used solely to supply the apparatus a part of which it is desired to earth. Provided that no conductor of an earthing system shall have a cross-sectional area of less than 0.022 sq. in.

(c) All joints in earth conductors and all joints to the metallic covering of the cables shall be properly soldered or otherwise efficiently made, and every earth conductor shall be soldered into a lug for each of its terminal connections. No switch, fuse, or circuit-breaker shall be placed in any earth conductor.

This rule shall not apply (except in the case of portable apparatus) to any system in which the pressure does not exceed low pressure (250 V) D.C. or 125 V A.C.

In the official Memorandum* on these Regulations, it is explained that—

(a) Although earthing is not compulsory, except in the case of portable apparatus where the pressure does not exceed the prescribed limits, it is nevertheless desirable where the pressure exceeds 50 V A.C. or 100 V D.C., if the surroundings are such as to provide a conducting path of low resistance to earth. With regard to the earthing system at the surface of the mine, this should be designed so that the resistance of the earth connection may be tested periodically without interrupting the circuit between earth and apparatus. At least two separate earth connections should be provided, and a permanent earth test panel on the main switchboard will be found a great convenience. The point of connection between earth conductor and earth plate should be open to inspection. If buried or otherwise hidden corrosion may proceed undetected until some accident occurs. Regarding the earthing of isolated motors in use above-ground, the Regulation does not specifically prohibit the use of more than one earthing system at the surface of the mine. If local earth-plates are relied upon it is even more important that their effectiveness shall be proved by periodical tests. A continuous earthing conductor is preferable, so that all apparatus may be earthed to the main earthing system. With regard to portable lamps, the lampholder itself, as distinct from the guard or other metal work, need not be earthed provided it is effectively shrouded with fireproof insulating material and is not in electrical contact with any other metal part of the fitting. All pendant lampholders, and especially switch lampholders, if they comprise exposed metal parts, should be earthed, even on systems falling within the exemption, if the floor or surroundings are of a conducting nature. For such places, however, it is better to use lampholders encased in insulating material.

(b) The acceptability of the metallic covering of a cable as the earthing conductor is subject to the condition that the cable shall comply with Regulation 129 (e) (§ 819 herein) which prescribes the construction and installation of armoured cables. These requirements comprise electrical continuity of the metallic covering, efficient protection against corrosion and a certain minimum electrical conductivity. It follows that all joints in the metallic covering must be efficiently and substantially made and that deterioration of the metallic covering must be guarded against. Metallic covering is defined in Regulation 118 to mean iron or steel armouring, and

* See first footnote to § 818 *supra*.

from this it follows that a plain lead sheath, or a copper sheath, cannot in the absence of iron or steel armouring be relied upon as the earthing conductor. The conductivity, however, of a lead-sheathed armoured cable may be taken to be the combined conductivity of the lead sheath and armour, provided that both are utilised effectively by suitable bonding at every point where the armour or the lead sheath is severed. Steel tape armour, which is relied on for mechanical protection for cables laid in the streets, will rarely be acceptable as an earthing conductor for apparatus to comply with this Regulation, because of its relatively poor conductivity. With tape-armoured cables some difficulty may be found in securing adequate conductivity at points where the armour is severed for the purpose of connection to apparatus and at joints. Flexible metallic tubing is sometimes used to enclose and protect insulated conductors; while such enclosure may afford adequate mechanical protection it does not constitute an adequate earthing conductor, and is not acceptable below ground as a substitute for armoured cable. The proviso, in the Regulation, of a minimum size of 0.022 sq. in. is important, and must be observed. . . .

(c) The necessity for proper attention to joints must be obvious. Metal parts constituting a joint should be thoroughly cleaned, and any glands or clamps should accurately fit those parts of the cable to which they are intended to make connection. Precaution should be taken to ensure the permanence of all such contact surfaces. Rusting of bolts or corrosion of surfaces may seriously reduce the value of the contact. A separate earthing conductor should never be attached to a bolt which also serves to fix the apparatus to its base, nor to a cover bolt, but it should be taken to an earthing terminal provided for that purpose. The connection must be permanently secure and dependable. The screw or other terminal on the apparatus for the earthing conductor should be of substantial dimensions and some form of locking device is generally desirable. Any discontinuity in the live circuit is soon evident, but an interruption, or point of high resistance, in the earth conductor may escape notice until the occurrence of an accident. The prohibition of a switch or equivalent device in any earth conductor does not exclude the use of a switch for testing purposes between the earth-plate and the neutral or mid-voltage point of the system, nor does it prevent the installation of switches to earth the neutral point of one generator only at a time when several are run in parallel.

Tests made by C. P. Sparks (*Journal I.E.E.*, Vol. 53, pp. 399 *et seq.*) indicated that more extensive earthing devices were necessary to safety than were suggested by earlier versions of the official Memorandum. It is not easy to make a satisfactory connection to earth below-ground even by an earth-plate buried in damp ground or in a water sump. An earth-wire, of section sufficient to carry the heaviest current which an accident may require it to transmit, is therefore taken to the surface and earthed there. Frequent testing is required to ensure that the path to earth remains unimpaired (§ 348, Vol. 1).

The Evershed earth-circuit continuity-tester has been developed to provide an instrument which will carry out the tests required by the Regulations; the instrument consists of a spring-controlled, single moving-coil indicator, graduated in ohms, with a cell of the

nickel-iron type and a pair of leads with testing spikes. The two ranges are usually from zero up to 0.5 and 0.05 respectively, by thousandths of an ohm. A current of about 5 A. is used on the lowest range.

All connections to cable armouring or other earth conductors should be in parallel (*never* in series), and the earth conductors must be electrically continuous and of low resistance; otherwise nominally earthed metal may attain a dangerously high potential. Where the conductivity of armouring is insufficient [Regulation 125 (b), *supra*] for earthing purposes a separate earthing cable may be used, but it is safer and more convenient to use a special earthing core in the cable itself. A good earth connection should be considered of even greater importance than good connections in the supply circuit, and the ohmic resistance of the whole earthing system, including all its connections, must be as low as possible. The use of insulated cable with its connection to the earth-plate embedded in insulating material is by no means a superfluous precaution to eliminate the risk of the actual earth connection being corroded away; enclosure in iron conduit prevents the connecting wire from being cut accidentally. Provision of two separate earth-plates permits of a resistance test from one to the other, and a multiple earth connection is further useful in limiting the temporary pressure rise occurring when a heavy earth current flows. The whole question of earthing in mines is discussed exhaustively by Sparks (*loc. cit.*), and among the points emphasised by this author is the desirability of making several earth connections by a coppering main connected to steam condensers, circulating-water and feed pipes, and other metal work in direct connection with earth. Where it is not possible to follow usual power-station practice in this respect, the contact area of each coke bed should be materially greater than specified by the old versions of the Memorandum on the Regulations, and the coke bed should be carried down at least 8 ft. below ground level. Tests show that the size of metal earth-plate is comparatively unimportant as compared with the area of the coke bed; to reduce the resistance of an earth connection, moisture should be supplied continuously, and the surrounding strata should be impregnated with salt at regular intervals (say of 1 month). If earth-plates are buried at insufficient depth, there may be dangerously high potential gradient at the surface when heavy current flows to earth.

822. Switchgear for Mining Work ; Motor Controllers.—Switchgear generally has been fully treated in Chapter 16 (Vol. 1); that used in colliery *power houses* follows the practice usual in central stations of similar capacity and using the same generating and distributing systems. Equipment of the steel plate cubicle type is very compact and reliable; remote control is generally adopted where the generator or feeder controlled is rated at 2 000 kW or over. Switchgear for use *underground* must be of quite special construction, and the primary requirements are that it should be very strong, reliable, flame-proof, and 'fool-proof.' The construction must be such that men in charge can see at once whether the switch is on or off, and the sequence of operations should preferably be automatic, so that when the handle is in the 'off' position it cannot be put into the 'running' position without passing through the 'starting' position; it must be quick-acting, contacts must be large enough for the heaviest currents to be carried (the effect of low P.F. not being overlooked in this connection), and liberal clearances must be provided in the break itself and between all live parts and the earthed frame or casing. The fact must never be overlooked that in the event of a short-circuit a single circuit-breaker, rated for its own apparatus only, may actually have to carry the far greater current of the short-circuit; *e.g.* a generator-breaker may have the whole station load thrown on it, with disastrous results if it is cut too fine. Accidental contact with live metal should be impossible, yet all parts must be easily accessible for inspection or repair. The draw-out type of totally-enclosed switchgear is superseding older types, each switch being completely isolated when drawn out. Any desired arrangement can be built up by assembling the separate units end to end. Often the switches are in chambers running out on bracket arms, or with a sliding carriage. Bus-bars should be enclosed in C.I. casings.

According to Regulations 127 and 128—

127. Switchgear and all terminals, cable ends, cable joints, and connections of apparatus shall be constructed and installed so that: (i) All parts shall be of mechanical strength sufficient to resist rough usage. (ii) All conductors and contact areas shall be of ample current-carrying capacity and all joints in conductors shall be properly soldered or otherwise efficiently made. (iii) The lodgment of any matter likely to diminish the insulation, and of coal dust on or close to live parts, shall be prevented. (iv) All live parts shall be so protected or enclosed as to prevent accidental contact by persons and danger from arcs or short-circuits,

fire, or water. (v) Where there may be risk of igniting gas, coal dust, or other inflammable material, all parts shall be so protected as to prevent open sparking.

123. (a) Properly constructed switchgear for cutting off the supply of current to the mine shall be provided at the surface of the mine, and during the time any cable is live a person authorised to operate the said switchgear shall be available within easy reach thereof. Lightning arresters, properly adjusted and maintained, shall be provided where necessary to prevent danger.

(b) Efficient means, suitably placed, shall be provided for cutting off all pressure from every part of a system, as may be necessary to prevent danger.

(c) Such efficient means shall be provided in respect of each separate circuit for cutting off all pressure automatically from the circuit or part or parts of the circuit affected in the event of a fault, as may be necessary to prevent danger.

(d) Every motor shall be controlled by switchgear for starting and stopping, so arranged as to cut off all pressure from the motor and from all apparatus in connection therewith, and so placed as to be easily worked by the person appointed to work the motor.

(e) If a concentric system is used, no switch, fuse, or circuit-breaker shall be placed in the outer conductor, or in any conductor connected thereto, except that, if required, a reversing switch may be inserted in the outer conductor at the place where the current is being used. Nevertheless, switches, fuses, or circuit-breakers may be used to break the connection with the generators or transformers supplying the electricity; provided that the connection of the outer conductor with the earthing system shall not thereby be broken.

Money expended on first-class switchgear of ample capacity is well invested, and may repay itself in a moment in case of emergency, when the difference between good switchgear and the best may be that between safety and serious breakdown.

'Ironclad' switchgear, with bare conductors enclosed in flame-proof compartments, is very suitable for underground use. The component parts should be so interlocked that the casing can only be opened after opening the isolating switches, and so that no metal can be made live till after it is effectively enclosed. Oil-immersion is an absolute preventive of open sparking at contacts, but is practically limited to A.C. gear, since D.C. maintains the arc and causes carbonising of the oil. Without oil-immersion, it is impossible to prevent ignition of explosive gases inside the casing and, as in the case of motors (§ 818), it is impossible to prevent such gas, when present, finding its way inside the casing. Consequently the casing must be strong enough to withstand internal explosions up to the maximum pressure (160 lb. per sq. in.). To limit and confine the effect of explosions occurring inside switch-boxes, preference should be given to designs which provide little free space in which gases may accumulate; for the rest, the casing must be strong and have wide metal-to-metal joints (without packing) permitting gas escape without propagation of flame (§ 812). At flanges and joints,

and where spindles pass through the case, the width must be at least 50 mms. and the gap not over 0·5 mm. Conduit should be taken into switch-boxes through flame-proof glands, otherwise there is danger of explosion being carried from box to box through the conduit.

Motor control generally, including liquid controllers, is dealt with in Chapter 29. Remote and automatic control is often possible underground, but the warning against delicate or easily deranged apparatus may be repeated here. Trips should operate to isolate any circuit in which the insulation fails. Automatic switches should be of the 'free-handle' type, so that they cannot be held 'in' on a fault. Usually an ammeter is all that is required in the way of instruments on motor-control or distributor panels below-ground; instrument transformers are to be avoided.

APPLICATIONS OF ELECTRICITY IN MINING.

823. Distribution of Power Demand.—Colliery owners in this country are required to advise H.M. Inspector of Mines of their intention to introduce fresh apparatus into any mine, and are also required to render an annual return, giving the size and type of apparatus in use and certain specified particulars concerning its use (Regulation 119). From the information thus collected annual summaries are published showing the aggregate horse-power of electric motors used for various purposes in coal and metalliferous mines. These summaries are generally to be found in *The Electrical Review*. Table 177 herewith* compares the figures for the years 1912, 1926 and 1931. Of 2 243 mines at work (in 1931) 1 409 used electricity, and there has been a remarkable increase in the application of power since 1921. Regional analyses of the figures will be found in the official Report.

824. Ventilation of Mines (*see also* § 826).—An ample and uninterrupted supply of fresh air is literally of vital importance in every coal mine. The load provided by the fans is considerable (*see* Table 177, § 823), and by reason of its high load factor it is very valuable to the power-station engineer, particularly in private generating schemes. A good deal has already been said concerning the power requirements of fans (§ 764) and the passage of air

* Reports of the Electrical Inspector of Mines, 1926 and 1931; also, *Journ. I.E.E.*, 378, p. 124 (Progress Report, 1927).

through ducts (§ 765), and the fundamental principles there laid down are equally applicable to colliery ventilation schemes. The points of chief present interest are the type of fan and motor to be employed, and the arrangements to be made for speed control. It may be taken that ventilating fans will always be driven electrically wherever current supply is available, owing to the convenience, efficiency, and reliability of this method, and the value

TABLE 177. — *Horse-power of Electric Motors installed for various purposes in all Mines governed by the Coal Mines Act, 1911; comparison between 1912 and 1926 and 1931.*

Purpose.	Horse-power of Motors Installed.		
	1912.	1926.	1931.
<i>Above-ground :</i>			
Winding . . .	23 895	182 569	160 307
Ventilation . . .	30 894	109 612	121 094
Haulage . . .	23 754	71 883	79 422
Washers and screens . .	43 570	182 234	166 569
Other purposes . .	71 975	321 802	345 223
Total above-ground .	194 088	768 100	872 615
<i>Below-ground :</i>			
Haulage . . .	130 025	356 727	398 944
Pumping . . .	144 318	365 191	397 332
Portable machinery . .	31 038	103 763	112 367
Other purposes . .	11 287	26 364	52 278
Total below-ground .	316 668	852 045	960 921
Aggregate Total . .	510 756	1 620 145	1 833 536

of the load in improving the average annual load factor. High-speed, centrifugal fans direct-coupled to high-speed motors form a much cheaper and more compact equipment than the large-diameter, steam-driven fans formerly standard. Owing to the extreme importance of continuous ventilation, it is generally desirable to install duplicate equipment; if this is not done for every fan, it must at least be secured that a certain minimum amount of air can be driven through the workings under any

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contingency humanly possible (*see also* § 825, *re* ventilation of motor rooms). Fans are generally in duplicate as a safeguard against breakdown and to enable repairs to be effected without interrupting the ventilation. Frequently one fan is driven electrically and the other by steam as a further safeguard.

A fan serving a fully developed section of the workings needs simply to be driven at constant speed day and night, with perhaps ten minutes or so stoppage at week-ends for overhaul; depending on the working programme and circumstances of the pit concerned, it may be possible to reduce the fan speed during the whole week-end period. Generally, however, a fan serves workings which are continually extending, so that during a period of three or four years the output of the fan must be increased at intervals till an additional fan and ventilating shaft are justified. A shunt or compound-wound D.C. motor (§§ 675, 677) may be used in either case, speed control being obtained by shunt field variation; but this involves installation of a rotary converter in the fan-house, unless the latter is so near the pit-mouth that it can be served economically from the D.C. mains generally provided there for lighting and variable-speed motor service. Synchronous A.C. motors (§ 679) are only suitable for fans requiring no speed variation and for cases in which the comparatively difficult starting of synchronous motors (§ 722) is no objection.* Generally, slip-ring induction motors (§ 683) are employed, possibly with the addition of phase advancers or power factor improvers (§ 695). Like some other A.C. motors, induction motors are inherently ill-adapted to speed control (§ 725); but where a fan is ventilating partially developed workings, the only alternative to wasteful throttle control of air supply is variable fan speed, and the long period during which reduced speed is required makes it essential that the speed reduction be obtained by efficient means. Comparatively coarse speed control is preferable, under these circumstances, to finer speed control but lower efficiency. Several alternatives present themselves. The fan may be driven through ropes instead of by a direct-coupled motor, the pulley ratio being changed from time to time; a small motor may then be used till the total air requirements justify installation of the full-power machine. There is no technical im-

*They are, however, particularly valuable in such cases for power-factor correction (Chapter 5) up to 0.80 leading, at full load (*Jour. I.E.E.*, 63, p. 522).

possibility in using a simple slip-ring motor with rotor resistance control, but the continuous loss in the rotor rheostat during the months or years of reduced-speed working represents prohibitive waste. Various systems have been devised to utilise the 'rotor-slip energy' in auxiliary motors or otherwise, instead of wasting it in I^2R losses. In the ordinary cascade system of control (§ 727) 'slip energy' from one motor is used in a second motor which adds its mechanical output to that of the first. In other systems A.C. commutator motors, motor-generator sets, and transformers are used in various combinations to render slip energy available as mechanical energy or as electrical energy returned to the mains. Though more complex equipment is required, such special systems are frequently justified by their effect in raising P.F. to unity and by the uniform speed gradation which they provide. In a certain case from practice, speed regulation from 10 to 25 % by rotor resistance gave a motor efficiency from 73 to 87 %, whilst various special systems of utilising the rotor-slip energy gave efficiencies from 83 to 94 % for the same power and speed range, in addition to raising the fan motor P.F. to unity.

In Bulletin No. 144 of the University of Illinois Engineering Experimental Station (July, 1924), Messrs. Arthur J. Hoskin and Thomas Fraser give formulæ for ascertaining the approximate H.P.-hours required for various mining purposes, which we quote in their appropriate paragraphs. For D.C. ventilation:—

$$\text{H.P.-hours} = \text{water-gauge reading at air shaft} \\ \times 5.2 \times q \times 24 / 33\,000 \times f \times e \times h$$

where q = cu. ft. of air circulated per minute,

f = fan efficiency (0.5 to 0.7),

e = mechanical efficiency of motor (0.85 to 0.87),

h = mechanical efficiency of engine-generator set (0.82 to 0.85).

For A.C. it is necessary to add in the denominator (where they are present) the efficiency of the motor-generator (0.82 to 0.85); the transformer (0.95 to 0.98); and / or the rotary converter (0.90 to 0.97).

825. Ventilation of Underground Motor Rooms.—Where large pumps are required, they may well be located in underground chambers hewn out for their accommodation. Ventilation of such chambers is an important consideration owing to the

considerable power dissipated as heat by high-power motors or transformers, even when of high efficiency. An underground pump room, for instance, may contain high-lift centrifugal pumps needing from several hundred to several thousand H.P. on full load. A 1 000 H.P. motor at 95 % efficiency loses 50 H.P. as heat, *i.e.* about 2 150 B.Th.U. per min. (§ 50), or enough to raise about 150 lb. or 2 000 cu. ft. of air per minute through 60° F. (taking the specific heat of air to be 0.24 and its weight 0.075 lb. per cu. ft.). If the mean temperature rise of the air be limited to 35° F. (corresponding, of course, to considerably higher temperature rise of the motor windings), the volume of air required for ventilation is $60 \times 2\,000 / 35$ or 3 450 cu. ft. per min. per 1 000 H.P. This corresponds almost exactly to the 10 000 cu. ft. per min. actually provided in a certain pump room containing motors totalling 2 900 H.P. Transformers are of higher efficiency than motors, and pump motors are the most powerful units installed below-ground, so that the ventilation of pump rooms is a more serious problem than that of ventilating other underground motor rooms or substations. Nevertheless, the same general considerations apply in all cases, and the above method may be used to estimate the volume of air required for ventilation. Air for this purpose should be drawn from the downcast shaft, and it is generally worth drawing it through filters by centrifugal fans, sheet-metal ducts being used as airways. By this means dust is prevented from accumulating in the motors and other equipment.

826. Pumping in Mines.—The importance of removing water from pits is second only to that of supplying fresh air to the workings, and, as shown by Table 177 (§ 823), pumping constitutes, in the aggregate, the most important electrical load in British collieries. Some pits are very dry, but others are equally wet, and it may be necessary to remove anything from 20 000 to 200 000 gallons of water per twenty-four hours from the workings. In the anthracite mines of Pennsylvania the conditions are far worse,* and it is reckoned that the average weight of water pumped is approximately 20 tons per ton of coal raised, with an average depth of about 500 ft., while during flood times it may rise to 100 tons per ton. Due to its magnitude, the pumping load can be made to exert a very beneficial effect on the load curve of the colliery as a whole.

* *Power* (New York), Vol. 66, Aug. 23, 1927.

For instance, the provision of large sumps may permit pumping to be confined to shifts in which no coal is raised. By thus limiting the pumping hours, the average pumping H.P. is naturally increased, and it is easy to arrange that the daily load curve is smoothed out considerably.* Even where the inflow of water is so great that continuous pumping is essential, it is possible to vary the rate of pumping to the advantage of the load curve. Where temporary cessation of pumping would result in flooding the workings, pumping sets and their supply mains must be duplicated, so as to reduce the risks of total breakdown to a minimum. Vertical-spindle centrifugal pumps, direct-coupled to waterproof motors, are convenient for use in sinking shafts, and various portable pumping sets are available for special purposes. For permanent pumping installations, multi-stage centrifugal pumps are compact and suitable for direct driving by high-speed electric motors; they are available for heads up to 2 000 ft. or more. Three-throw plunger pumps electrically driven through single-reduction gearing are sometimes preferred to the centrifugal type. A rough rule bearing on this matter suggests that rotary pumps be preferred where the gallons to be raised per minute equal or are greater than the head (in feet), whilst ram pumps be used where the gallons per minute are less than the head in feet. (*See also* §§ 768 *et seq.*)

Pumps capable of working when totally submerged were developed originally for marine salvage work, and are also applied in mining both for de-watering drowned shafts and for dip workings where the water level is liable to unexpected variations. In these the windings are waterproof and the rating can be extremely high, owing to the heat being carried away by the water from the motor.

The automatic operation of mine pumps † is in use in America. With plunger pumps this offers no difficulty, as they are self-priming; and the same remark applies to turbine or centrifugal pumps when they are permanently below the intake level. Where this is not so, automatic apparatus has been designed to fulfil the double function of starting and priming when the water level renders it necessary.

Messrs. Hoskin and Fraser ‡ give the following formula for finding the H.P.-hours required in D.C. pumping:—

*In Fig. 51, § 266 (Vol. 1), a sewage pumping load, which is analogous, is included in the load curve to illustrate the good diversity and load factors.

†*Power* (New York), Aug. 23, 1927.

‡*See* reference in § 824.

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$$\text{H.P.-hours} = \text{Gal. per day} \times 8.3 \times \text{depth in ft.} \\ \times r / 60 \times 33\,000 \times p \times e \times h,$$

where r = water-pipe resistance factor,

p = pump displacement; percentage of theoretical (60),

e = mechanical efficiency of motor (0.85 to 0.87),

h = mechanical efficiency of engine-generator set (0.82 to 0.85).

For A.C. it is necessary to make the additions referred to in § 824.

827. Winding, General.—The only reasonable conclusion to be drawn from the mass of arguments and data published during the past twenty years or so concerning the relative merits of steam and electric drive for pit-shaft winding gear, is that neither system is invariably the better. Where there is already a reasonably good steam winding engine at work it is difficult to make out a commercial case for electrification; the best course in such a case may be to install mixed-pressure turbo-generators (§ 817) to utilise exhaust steam from the winding engine; but this is merely a palliative which ‘perpetuates wasteful machinery and only reduces the waste,’ as Mr. Woodhouse remarked in his inaugural address to the I.E.E. (1924). Where a new shaft is concerned, the points to be borne in mind are that electric winding gear is costly (including a due proportion of the power-house outlay, the cost is sometimes estimated as twice that of steam winding gear), but, on the other hand, electric winding reduces stand-by losses and effects notable economy during acceleration and retardation periods. Electric winding therefore shows to special advantage where the load and plant factors are low and where accelerating and retarding power is particularly important owing to winding gear being heavy or the winding depth shallow. Maximum rope speeds up to 4 000 ft. or more per min. are obtainable by electric winding; the latter permits with economy a higher average winding speed than is possible with steam winding, particularly in shallow shafts, and it is easy to arrange a complete and automatic series of safety devices where electric winding is practised. Conditions vary so widely that the probable annual cost of steam and electric winding should be estimated carefully for each particular pit, taking full account of the proposed working schedule and the incidence and magnitude of other loads. There are few if any cases in which effective comparisons can be made between existing steam and electric

winding installations; if such be attempted they should be based on as long a period as possible, say on annual totals and averages. Well-established advantages of electric winding are savings in brake and rope maintenance; simple control; fuel economy (in most cases); and increased coal-output per shaft (a very important consideration).

Winding may account for from 20 up to 70 % of the total colliery load, according to the depth of the shaft, the output and the stage of development reached; the load is necessarily intermittent and very variable, with high peaks and a bad load-factor. Messrs. Hoskin and Fraser * give the following formula for finding the H.P.-hours required for D.C. hoisting:—

$$\text{H.P. hrs.} = \text{daily tonnage (short ton)} \times 2\,000 \times \text{hoisting depth (feet)} \times s / 33\,000 \times 60 \times e \times h,$$

where s = shaft resistance factor (1.05),

e = mechanical efficiency of motor (0.85 to 0.87),

h = „ „ of engine-generator set (0.82 to 0.85).

For A.C. it is necessary to make the additions referred to in § 824.

The efficiency of winding depends on a number of factors; on the shaft efficiency; number of conversions between supply and rope, including generator, gear, sheaves, etc.; rheostatic and other control losses; form of winding cycle and depth of wind, affecting the ratio between full power periods and control or braking periods. Theoretically (at 100 % efficiency) 1 kWh will raise 1 185 ton-ft., equivalent to 0.845 kWh per 1 000 ton-ft.† In practice, taking the product of the depth by the net or unbalanced tons hoisted, it is found that the average consumption in main shaft winding varies between $1\frac{1}{3}$ and 2 kWh per 1 000 ton-ft., the higher figure applying to short, fast winds where acceleration is responsible for an unduly large proportion of the total. The efficiency therefore ranges between 42 and 63 %. The means by which may be calculated the 'shaft H.P.' theoretically required is explained in paragraph 831. Theoretically, the kWh consumed by the winding plant = $0.75 \times \text{shaft H.P.-hr.}$ (assuming 100 % efficiency); actually, up to 1.5 kWh per shaft H.P.-hr. may be required by modern electric winding equipment (2 kWh per shaft H.P.-hr. indicating too low efficiency). Tests made on the

* See reference in § 824.

† Ton of 2 240 lb.

Continent a few years ago indicated that a number of modern steam-winding installations used 30 to 60 lb. steam per shaft H.P.-hr., and that (Lb. steam per shaft H.P.-hr.) = $15 \times \text{kWh}$ per shaft H.P.-hr. On the latter basis of conversion, $1.5 \text{ kWh} = 22.5 \text{ lb. steam per shaft H.P.-hr.}$, which is less than observed in any of the steam installations tested, and thus justifies the claim made for fuel economy obtainable by electric winding.

The various systems of electric winding and the allied problem of flywheel storage (§§ 828-9) are worth dealing with in some detail, because the difficulties encountered and the means whereby they may be overcome are common to other heavy and fluctuating industrial loads, *e.g.* rolling-mill drives (§ 778). Both D.C. and A.C. motors are used to drive winding gear; D.C. machines are preferable in respect of starting characteristics and speed control (*see* Chap. 28), whilst A.C. motors operate directly on the supply system found most convenient for generation and distribution for industrial purposes (§§ 465, 814). The power required for winding purposes is so considerable that one may safely assume supply to the winding house itself to be in the form of 3-phase, high-pressure A.C. This supply may or may not be converted to D.C. for the winding motor according to which of the following systems is employed. The simplest arrangement consists of a 3-phase induction motor, direct coupled or (better) geared to the winding drum, and controlled by variable rotor resistance (§ 723). Mechanically, this arrangement is simple and efficient, but the ohmic losses in the control-resistances are serious, and the full 'peak' load on starting and accelerating (§ 831) falls directly on the mains, hence this system is not recommended for large winding gear.

Liquid controllers (§ 739) of the lifting electrode or, preferably, of the weir type are used; the latter having advantages in regard to setting the maximum acceleration. Slip-ring motors are generally used, but the cascade motor has advantages in the matter of starting torque, efficiency and low starting current. When supply is taken from a large-power network, direct-geared winding motors may be permissible up to 500 or 600 H.P., corresponding to peak loads of say 1 500 H.P. For larger sizes of winder, with higher speeds consequent on greater depth of shaft, the *Ward-Leonard system* of control (§ 716) is most often used, as the increased efficiency is found to offset the extra cost, and

automatic control from the depth indicator is possible. (*See also* next para.). According to Stjernberg,* if the value of $MS / (QT^2)$ exceeds 0.22, Ward-Leonard control is preferable and above 0.3 indispensable, where—

M = equivalent mass reduced to rope
 = weight in lb. / gravity coefficient,
 S = depth of shaft in feet,
 Q = useful load + friction, in lb.,
 T = net time of wind in seconds.

The position, however, is rapidly altering in view of the far greater capacity of modern power companies' generating stations and the policy of inter-connection. In his inaugural address as President of the I.E.E.† Mr Woodhouse remarked :—

'In the past, moreover, a public supply on a sufficiently large scale was rarely available, and the special devices necessary to reduce the peak loads were costly. To-day, in all the principal coal fields, a public supply is available on a scale which no longer need be concerned with the variations of load, and the simplest type of motor may be fitted and supplied from the general system without difficulty.'

828. Winding ; Flywheel Storage.—Peak demands equal to two or three times the mean H.P. have inevitably to be supplied at the winding drum during accelerating periods, and when these peaks amount, as they frequently do, to something of the order of 2 000 or 3 000 H.P. means may have to be taken (in some cases) to relieve the central station and transmission line of the adverse effect of such loads on voltage regulation and section of copper required. Buffer batteries might be used, but flywheel storage (§ 751) is better suited to the loads and general conditions concerned.

This is well illustrated by the normal H.P.-time diagram (Fig. 391) of the Metrovick 3 000 / 7 500 H.P. double-motor, D.C. winder, with Ward-Leonard control and flywheel set, installed at one of the collieries of the Carlton Main Co. near Doncaster.‡ At the time of its installation, this was the largest in Great Britain ; the following details are quoted from the source mentioned :—

* *Journal I.E.E.*, Vol. 46, p. 192 *et seq.*

† *Ibid.*, Vol. 63, p. 4.

‡ *Metropolitan-Vickers Gazette*, Vol. 10, No. 177, and *El. Review*, December 16, 1927, p. 1025.

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The shaft at which the equipment is installed was a new one, and the winder was first used for sinking operations. The main working conditions to which the winder was designed are as follows:—

Depth of shaft	2 610 ft.
Weight of cage and chains	17 196 lb.
Weight of one tub	728 lb.
Net load of coal per cage	14 780 lb.
Output per hour	300 tons
Type of rope	locked coil
Diameter of rope	2 ins.
Type of drum	Bi-cylindro-conical
Small diameter of drum	16 ft.
Large diameter of drum	26 ft.

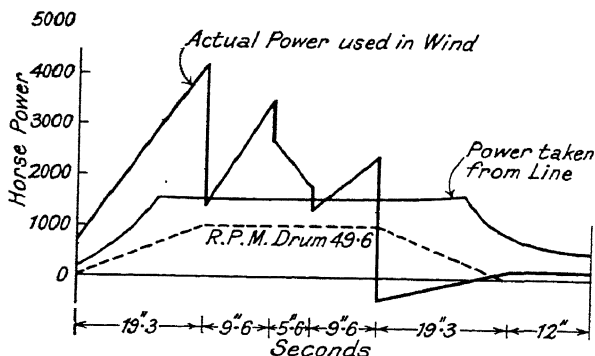


FIG. 391.—H.P.-time diagram for winder under normal load.

The two winder motor units are disposed on either side of the drum. They are open type machines with commutating poles and separately excited shunt field. Each unit is 13 ft. 4 ins. in diameter and weighs 67 tons. They operate at 49.6 r.p.m. in series connection on a 1 000 V supply from the motor-generator set. The normal H.P. / time diagram for the motor is shown in Fig. 391, which gives a striking indication of the effect of the flywheel in eliminating the peaks, so as to obtain an approximately constant load demand throughout the wind. The set is capable of dealing with a maximum peak of 7 500 H.P. and of sustaining an overload of 25 % for two hours. The connections of the machines are so arranged that in case of emergency the winder can be driven by one motor and on the supply from one generator of the motor-generator set.

The motor-generator set consists of a slip-ring induction motor of 1 540 H.P. driving two 1 065 kW, 500 V direct current generators connected in series, and a solid steel flywheel of 23 tons weight and 12 ft. diameter, mounted between the generators. The induction motor is of the open protected type, with inside slip-rings and brushgear suitable for continuous running. Its synchronous speed is 750 r.p.m. The generators are of the open compensated type. Their overload capacity after six hours' full load run is 25 % for two hours, or a momentary peak of 4 240 kW total for the two machines.

The flywheel is of the Metropolitan-Vickers special disc type, of cast steel. It is unpierced at the centre, being carried on two jack shafts which are attached to the wheel by spigotted flanges, arranged so that the torque is transmitted through keys and not through the fixing studs. The wheel is provided with a planished steel guard over its upper part, while the lower portion runs in a pit in the foundation. In this way air resistance is reduced to a minimum. The energy delivered by the wheel during a 15 % drop in speed is 45 000 H.P.-secs.

The principle employed in all flywheel storage systems is that a flywheel is brought up to speed during periods in which the working load is less than normal, and is slowed down during periods in which the working load is greater than normal. Whilst being accelerated, the flywheel absorbs energy and thus fills in the 'hollows' of the curve representing the demand on the supply mains; and, on the other hand, whilst being retarded, the flywheel gives up some of its stored kinetic energy and thus lowers the 'peaks' of the net demand curve. When it is a question of dealing with hundreds or thousands of horse-power, very heavy flywheels must be used, and they must be driven at the highest safe peripheral speed (since the energy stored varies with the square of the speed). Cast wheels may be run at 17 000 ft. per min. in large sizes, up to 23 000 ft. per min. in small sizes; whilst disc wheels built of armour plate may safely be run up to 25 000 ft. per min. or even faster. Flywheels used in connection with the winding equipments described below are often 6 to 14 ft. in diameter, weigh 5 to 30 tons, and store sufficient energy to permit two or three winds to be made with full load after current supply has been interrupted by some mishap. Bearing and windage losses associated with running such wheels at very high speed are by no means negligible, and, during shifts in which little winding is to be done, it may pay to shut down the flywheel set and work at suitably reduced speed without 'equalising' the demand. The following notes concerning the predetermination of flywheel size are instructive.

The most convenient method of calculating the sizes of the various machines is to take first the load diagram; thence the size of winding motor follows at once (knowing its overload capacity and the mean H.P. required). The generator may be made 10 % larger, since it has to supply the motor losses. Add to the load diagram the instantaneous losses on the whole cycle. When the winding motor returns energy during retardation, the motor-generator losses must be subtracted from the load diagram. This gives the generator-input diagram and hence the induction motor input. The total H.P.-secs. input is calculated from the various loads and their duration, and this total divided by the time per trip (including banking periods) gives the average input. Loads in excess of this average are taken by the flywheel.

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The weight of the flywheel in lb. = $35\,400 \times \text{flywheel output (H.P.-secs.)} / [(\text{max. veloc.})^2 - (\text{min. veloc.})^2]$, both velocities being taken at the radius of gyration (= $0.707 \times \text{radius}$, for disc wheel). The flywheel output is that calculated from the output diagram. The output demanded by the induction motor will be [mean load as found from the diagram + windage and friction losses + average slip-regulation loss (i.e. half the maximum loss) + power required to drive the exciter]. In calculating the bearing friction, the coefficient of friction may be taken as 0.004. The windage loss (in H.P.) for smooth, uncased wheels = $0.051\,3\,V^{2.5} \times 0.093\,D^2 (1 + 0.465\,B^2) / 10^5$, where V = peripheral speed, ft. per sec.; D = wheel diameter, ft.; B = wheel width, ft. (*G.E.C. Mining Bulletin*).

Enclosure by a suitable casing materially reduces windage losses at high peripheral speeds. Flywheel storage shows to best advantage where winding is frequent and from shallow depths; acceleration and deceleration periods then form a maximum percentage of the total working time, and losses in the 'equalising' apparatus become of minimum importance.

829. Winding Systems utilising Flywheel Storage.—Using an induction motor, geared directly to the winding-shaft, the simplest method of applying flywheel storage is to drive a suitable flywheel (chosen as above) by a shunt-wound D.C. motor, the latter being supplied from the A.C. mains through a rotary converter and, if necessary, a step-down transformer. It is arranged that, when the demand on the A.C. mains reaches a predetermined maximum, the field of the flywheel motor is strengthened; this causes the flywheel set to slow down, the motor meanwhile acting as generator and returning energy, through the rotary converter, to the mains. During light-load periods the field of the flywheel motor is weakened automatically and the flywheel is consequently accelerated. The maximum H.P. demanded from the mains is the difference between the peak winding-H.P. and the H.P. developed by the equaliser set. This system of 'equalising' does not preclude winding at reduced load or speed without flywheel storage, should the equaliser set break down. A further advantage is that the rotary converter can be operated at leading P.F. to correct for lagging P.F. in the winding motor. The equaliser set need not be placed near the winding motor (though the length of circuit in which the 'peak' current circulates should be a minimum); it may serve several winders if desired.

The *Ignner winding system* is estimated to be used in more than 75 % of large balanced electric winding equipments. It consists in a combination of the *Ward-Leonard system* of D.C. motor control (§ 716) with flywheel storage. The whole supply

for the winding motor is taken through a motor-generator, consisting of a 3-phase motor and a D.C. generator, the latter capable of field, and therefore voltage, regulation from zero to a maximum positive or negative (say ± 600 V). The generator is permanently coupled to a separately excited D.C. motor, so that any winding speed from 'inching' (for shaft inspection) up to the maximum in either direction is obtainable by varying the generator field. A flywheel on the motor-generator shaft equalises the demand on the mains. Speed reduction of the flywheel set (to permit the flywheel to yield its stored energy) is obtained by increasing the slip of the motor driving the set. The obvious method of doing this is to insert rotor resistance automatically, as the demand of the winding motor increases; but it is better to utilise the slip-energy in an auxiliary A.C. commutator motor (returning energy to the line or adding its output to that of the motor controlled, § 728), rather than dissipate it as heat in ohmic losses. In addition to improving the P.F. of the induction motor, this system of control saves about 90 % of the energy otherwise wasted in slip resistances, and gives the induction motor the characteristics of a D.C. compound-wound machine. Where slip resistances are used they may conveniently be of the liquid type: there are various methods of operating the rheostat switches, one being by means of an induction motor connected to the secondary of a transformer, the primary of which is in the main circuit. Since the energy stored in a flywheel varies with (velocity)², the output of the flywheel varies with the difference between the *squares* of its initial and final velocities (and *not* in direct proportion to the slip of the motor driving the equalising set). The greater the slip, the lighter the flywheel required for specified equalising effect, but also the greater the slip losses, if simple rheostatic control be employed. The more frequent the winds, the more serious are slip-regulator losses, and the less serious are the friction losses in the flywheel converter set.

Speed control and reversal of a winding motor operated on the Igner system are entirely by variation in the D.C. generator field, and the main control lever, brakes, and other parts of the equipment are so interlocked as to secure absolute safety. For instance, the main control lever is interlocked with a depth indicator so that overwinding or too rapid acceleration are impossible; full current cannot be applied to the winding motor whilst the brake is full on, and conversely the brake cannot be applied while full current is

flowing; the emergency brake—which may be applied by hand; by failure in the air pressure which normally holds it ‘off’; by overwinding; by serious overload; or by interruption in current supply—cannot be reset till the controller is ‘off’ and the working brake ‘on.’

The great disadvantage of the Ilgner system is that it involves two auxiliary machines, each of which must be of the same capacity as the winding motor itself; also, a breakdown in the converter set makes winding impossible except as regards the one or two winds which may be performed by the energy stored in the equaliser flywheel. Where D.C. supply is available, a flywheel motor-generator or booster set may be used in series with the winding motor to admit a gradually increasing E.M.F. to the latter on starting. The auxiliary set carries the full winding current, but is wound for only half the supply voltage, and is therefore a much lighter and cheaper equipment than the converter set needed by the Ilgner system.

In high-power winding gear operating on whatever system, the use of two winding motors, one on each side of the drum, is convenient, and increases the reliability of the installation; only one of the two motors need be installed when first starting work in the pit concerned.

830. Steam-electric Winding: Stubbs-Perry System.—A departure entered upon at the Harworth Colliery (Notts.) is believed by Professor D. Hay* to have great possibilities where no outside source of electricity supply is available. In this, the Stubbs-Perry system (installed by the Metropolitan-Vickers Co.), the winding is entirely separated from the remainder of the colliery load; and the Ward-Leonard system is modified by the substitution of a geared turbine drive to the D.C. generators in place of the motor-generator set. The turbine has a high range of speed, and a small flywheel-balancer is used to help over the peaks, the whole being simple and easy to control. The remainder of the colliery is operated from separate turbo-generators, which are therefore unaffected by the winder peak-load.

831. Haulage.—Much of the information given in Chapters 34 and 35 is also applicable to mining traction problems, in which, be it noted, the worst conditions of greasy, wet, and uneven track

* *Proc. Inst. C.E.*, Vol. 223, p. 196.

have to be faced. Five distinct rope-haulage systems are main haulage, main and tail haulage, endless rope haulage, endless chain haulage, and haulage by locomotives (§ 832).

In *main* (also known as *direct-acting* or *dook*) haulage, the haulage motor is placed at the head of a gradient (not less than 1 in 20) up which tubs are hauled and down which they return by gravity. Only a single track is used; very high starting torque is required to start and accelerate the train of tubs uphill, and smooth starting is essential to reduce the stress on rope and couplings.

Main and tail haulage is practised on level or only slightly inclined roads, or where the roads are undulating. The tubs are pulled in both directions of travel—first by the main rope, then by a tail rope running round a sheave at the far end of the road. The two ropes are carried on two drums mounted on the same shaft at the motor end, and engaged by a dog clutch, one drum being allowed to run free as the other is engaged. High starting torque is again demanded, as a double length of rope has to be hauled. Only one track is required, which is an advantage in poor roof conditions, also in shallow seams where bottom stone has to be cut out to provide headroom in the roadways.

Endless haulage employs an endless rope or chain running continuously round end sheaves, coming over one track and returning over a second line of rails, so that continuous working may be carried on all round the loop. This system eliminates frequent starting and stopping, reduces wear and tear, and gives a much better load factor than the other systems.

A main or main and tail haulage may be driven by a D.C. compound motor (§ 677) or by a slip-ring induction motor (§ 683) with liquid starter and controller (§ 739). Instead of starting and stopping the motor for each haul, a mechanical clutch may be provided and the motor kept running; this is especially advisable where an A.C. motor is used. A squirrel-cage motor with star-delta starter (§ 724) and friction clutch forms a satisfactory drive for endless haulages. Single- or double-reduction gearing between motor and haulage drum is often justified by the resulting saving in size and cost of the motor.* D.C. motors are inherently better adapted than A.C.

* Prof. D. Hay has stated in a lecture that mining engineers 'are only just arriving at the stage of anti-friction bearings and high-efficiency enclosed gearing,

machines to haulage work, in starting and in point of speed control and automatic speed reduction on gradients or with heavy loads. Where liquid starters and controllers (§ 739) are in fairly continuous service it may be necessary to arrange for a circulating and radiator system or for a supply of cooling water.

Main haulage generally works at a speed of about 6 m.h.p., while main and tail works at nearer 10 m.p.h. Some years ago Mr. Williams-Ellis* gave what he described as a typical instance of the economy of electric over steam haulage. On a road 500 yds. long the working cost by steam was 1.77d. per ton, whereas with electric haulage substituted it came down to 0.39d. per ton, on an output of 300 tons per day—a saving of £500 per annum. Similarly, he quotes Messrs. Greaves' slate quarries (N. Wales) where a battery loco. saved £400 per annum over horse traction.

Next to pumping, haulage represents the chief electric power demand in British collieries (Table 177, § 823), but unfortunately it is one of poor load factor (often about 5 %). The strain on a rope hauling a load of w lb. up an incline of angle θ is ($w \sin \theta$ + an allowance for friction). If the load be 10 000 lb. and the lift vertical, as in winding, the strain is 10 000 lb.; but if the gradient be 1 in 1 (*i.e.* $\theta = 45^\circ$, $\sin \theta = 0.707$), the strain is 7 070 lb. *plus* rolling friction (§ 879).

For steel wire ropes the factors of safety generally adopted are as follows: Aerial ropeways, $4\frac{1}{2}$ to 6; suspension bridges, 5 to 7; cranes and hoists, 7 to 9; slings, 5 to 7; haulage, 7 to 9; winding, 8 to 10. The breaking strain may be as high as 120 tons per square inch.

If the speed be 5 m.p.h. (440 ft. per min.), the power required in the above two cases will be: *Vertical lift*— $10\,000 \times 440 / 33\,000 = 133$ H.P., or, allowing 20 % for friction, a motor of about 160 B.H.P. would be required. *Gradient 1:1*— $10\,000 \times 0.707 \times 440 / 33\,000 = 94$ H.P., but in this case there is rail friction as well as friction in the haulage gear, so that about 30 % extra power would be required, say 125 to 150 B.H.P. at the motor. On a 1 in 10 gradient, the power required would be 18 to 20 B.H.P. (*Note.*—Gradient = rise in ft. / horizontal distance

in place of noisy open-running machine-cut gears. There is no reason why the mechanical efficiency of haulage gears should not be 90 % and the noise as nearly nil as possible.'

* *El. Review*, Sept. 30, 1921, p. 428.

= $\tan \theta$; the corresponding sine may be read from the usual trigonometrical tables.)

Useful tables relating to the power required by haulage and winding are to be found in the *Electrical Trades Directory*; those given by Mr. W. C. Mountain may be calculated from the following formulæ:—

Main and Tail Haulage at 10 m.h.p.—

$$\text{H.P.} = 1.67 \times \text{tons load} \times (\text{incline} + 2).$$

Endless Rope Haulage on 1 000 yds. of road—

$$\text{H.P.} = \frac{\text{Coal output (in lb. per min.)}}{400} \times (\text{incline} + 2).$$

In both these formulæ the incline is expressed in *inches per yard*. In the case of main and tail haulage the load includes the weight of coal, tubs, and ropes; and the horse-power may be taken to be directly proportional to the speed. As regards endless rope haulage, the incline is the average rise (*i.e.* total rise in inches / total yards of road), and the horse-power may be taken to be directly proportional to the length of road. In both cases the above formulæ provide a reasonable margin to cover friction.

832. Pit Locomotives.—*Trolley locomotives*, as an alternative to other systems of main haulage, in no sense replace pit ponies, but *battery locomotives*, used for gathering service, may do so. Many types of *trolley locomotives* are in use for both surface and underground haulage on the Continent and in the United States, but are prohibited in British mines without special sanction. The locos by which much of the haulage is done in America are usually of the D.C. series-motor type, one-hour rated, operating on 240 or 480 V. They vary in weight from 4 to 35 tons, and use gauges from 18 ins. to 4 ft. 8½ ins. In this country trolley locos are not allowed in coal mines (without special sanction) owing to the risk of explosion caused by open sparking and owing to the risk of shock inseparable from the introduction of bare trolley wires (*Regulation 136 (a)*).

Compressed-air locomotives have not found extensive application, owing to the weight of the storage cylinders and the re-charging and maintenance delays and costs involved.

Accumulator locomotives are permissible, although they suffer from analogous disadvantages, but their use is steadily (though slowly) extending; they may necessitate modification of

the pit roads, so as to permit the use of the most suitable type for the work rather than a compromise designed to suit the existing roads. The £1 000 Markham competition in 1925 for the best battery locomotive, conforming to the requirements of an *ad hoc* Committee, was designed to stimulate this field of progress but does not appear to have led to any very notable results. A full account of the various locos (all of British make) tested in the competition will be found in the technical Press * of 1925, but a few points may be mentioned here. The prize was awarded to Messrs. Joseph Booth & Bros. of Leeds, whose 'Union' design included some novel features. The cells are mounted in groups, in hardwood crates enclosed in steel boxes, which are in turn supported on rollers mounted in the loco frame; they are locked in by a patented device, and attached to the circuit through plugs and sockets, so that a battery can be rolled out and replaced in less than five minutes. The frame consists of two parts, a chassis containing the whole of the mechanical gear and a second unit, spring-borne on the chassis, containing the whole of the electrical gear; the latter can be unhitched by unskilled labour when necessary and replaced by a spare part. A single four-pole motor is used, driving through a flexible coupling and cardan shaft; and the machine is capable of hauling a load of 5 tons on the level at 6 m.p.h. or 20 tons at 3 m.p.h., with a starting pull of 2 000 lb.

In connection with this, Mr. L. Millar has summarised † the requirements of a battery loco for gathering purposes in thin seams (where the conveyor is unsuitable) and for marshalling purposes at the junction of haulage roads:—

- (1) The height, width, and length of the loco are limited. These must conform with the dimensions which can be accommodated in the gate roads or the cage.
- (2) The weight is limited to that which can be safely handled in the cage or in case of a derailment.
- (3) Ample clearance must be allowed underneath the loco to clear obstructions on the main haulage road, such as tub greasers, pulleys, and other devices for controlling the tubs.
- (4) The loco must also be capable of giving sufficient adhesion to pull at least a load of 5 tons on a gradient of 1 in 20 and have a speed on the level of about $3\frac{1}{2}$ m.p.h. when pulling the same load.

* *El. Review*, Oct. 2, 1925, p. 529; Oct. 9, 1925, p. 564; *Electrician*, Sept. 25, 1925.

† *Jour. I.E.E.*, Vol. 64, p. 1004.

(5) The wheel base of the loco must be such that the loco is capable of going round a curve of about 12 ft. radius. The overhang when negotiating the curves must be such as not to foul the sides of the gate road.

(6) The whole of the electrical equipment must, of course, be flame-proof and of a type which it is safe to work near the coal-face. It must, in addition, be capable of being worked in the open air with rain falling, and of being operated through a considerable depth of water without permanently affecting in any way the sanding gear or electrical equipment.

(7) It must be possible to change the battery quickly.

As regards flame-proof construction (§ 812), reference may be made to the B.S. Specification No. 229 and others mentioned in the Bibliography. The sanding apparatus is of great importance in obtaining good adhesion: the writer quoted above states that 'the figure of 0.25 for the coefficient of adhesion can as a rule be considerably improved at starting, and 0.3 is frequently used.' The rolling resistance of the load may be taken as of the order of 50 to 60 lb. per ton (*cf.* corresponding figure of the traction coefficient in § 879, Chap. 34) according to Mr. Horsley.*

There are no less than 56 different gauges in use—a case ripe for, and taken up by, the B.S.I.—though the 2-ft. gauge is easily foremost.† A capacity of about 12 kWh at the 5-hrs. rate is indicated, with a voltage not exceeding 80 V, the batteries being in duplicate, so that they can be interchanged for charging at each shift. Either one or two motors, aggregating about 8 H.P., may be used; the latter having the advantage of obviating resistance control and the former of higher efficiency owing to its larger size. The drive may be by double-reduction chain, double- or single-reduction spur-gear or enclosed worm. Roller bearings offer difficulties in the way of maintenance in the dust-laden atmosphere, but show a very great saving in power consumption—namely, about 20 % over all.

Tests conducted on the Continent a few years ago showed the following energy consumptions (at the power house) per gross ton-mile and per useful (coal) ton-mile respectively: 0.13 and 0.20 kWh for trolley locos; 0.25 and 0.37 kWh for accumulator locos; 0.65 to 1.3 and 1.25 to 2.5 kWh for compressed-air locos. Though the exact figures will vary in different cases, these express the relative efficiencies of the three systems with reasonable accuracy. The power required *from the battery* in that type of loco was found in

* *Jour. I.E.E.*, Vol. 64, p. 1015.

† B.S.I. Report C.A. (C.R.) 9295.

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one case to be equivalent to a consumption of 0·16 kWh per ton-mile. Accumulator locos are roughly twice the price of trolley locos of equal power, and tests conducted a few years ago showed the total operating costs per ton-mile (including capital charges) to be 2 to 2½ times as great for accumulator as for trolley locos, according to the working hours per shift. The corresponding figures for compressed-air locos were 1·3 to 1·7 times the total operating cost of trolley locos.

Messrs. Hoskin and Fraser* give the following formula for finding the H.P.-hours required for haulage by locomotives (D.C.):—

$$\text{H.P.-hrs.} = w \times 2\,000 \times v \times \text{operating time (hrs.)} / d \times 33\,000 \times e \times t \times h,$$

where w = weight of loco in short tons;

v = average speed in feet per minute (main haulage \pm 352; gathering \pm 264);

d = draw-bar pull as fraction of loco weight (about 1/9 on main haulage);

e = mechanical efficiency of motor (0·85 to 0·87);

t = transmission efficiency (0·78 to 0·85);

h = mechanical efficiency of engine-generator set (0·82 to 0·85).

For A.C. it is necessary to make the additions referred to in § 824.

833. Compressed Air versus Electricity; Air Compressors.†—Compressed air must be admitted to be inherently a safer medium than electricity for power transmission underground, but it is a simple matter to apply automatic safeguards to all electrical equipment, and official returns prove conclusively that electricity is responsible for a very small percentage of colliery accidents. In point of efficiency (*see infra*), electrical working is undoubtedly superior; the energy consumption in the power house is often four

* See reference in § 824.

† The relative merits of these agents are compared by Mr. Sam Mavor, 'The Applications of Machinery at the Coal Face,' *Jour. I.E.E.*, Vol. 64, p. 989. Also, a paper by Prof. D. Hay and N. E. Webster, contributed to the Second World Power Conference, Berlin, 1930, drew a comparison between compressed air and electricity for use in collieries, the economic and practical working standpoints being considered. While these authors recognised the convenience of compressed air and its suitability for percussive tools, they were of the opinion that most of the power services of a colliery could be carried out much more economically by electricity. They also pointed out that successful types of electrical heading machines, giving a combined reciprocating and rotary motion, had been introduced.

or five times as great with compressed air distribution as with electrical transmission and electric driving in-by. After balancing inefficiency against the fact that compressed air cannot promote an explosion, there remains the important advantage that it assists ventilation while performing its work; and in the percussive rock-drill (§ 836), the supremacy of air is no more than threatened. But as in the case of gas and electricity, so here the rivalry between the two forces is showing signs of turning to co-operation, as the great losses in long air pipes can be eliminated by using electrically-driven compressors near the working face. Serious leakage occurs from the average compressed air pipe-line, particularly from temporary and flexible piping near the working face. Even if compressed air be used for coal cutters, conveyors, drills, etc.—whether on grounds of safety, or for the sake of cooling and ventilating headings, or for other reasons—the air pipe-line may be kept short by using stationary or portable electrically-driven air-compressors underground.

On the other hand, large compressors installed in the pithead power house operate under more favourable conditions in respect of freedom from dust, ease of maintenance, and smaller reserve plant requirements. These considerations may outweigh the losses in the extra length of piping involved. Central compressors may be operated in conjunction with storage tanks fitted with automatic 'unloading' valves. As far as possible, the compressor output should be regulated automatically by varying the speed of the driving motor according to the demand for air, but the unloading valve is needed in the event of the demand for air falling temporarily short of the supply even with the motors at their lowest speed. Slip-ring and cascade induction motors (§§ 683, 694) are sometimes used to drive central air compressors, but D.C. motors are preferable in respect of easy speed control over a wide range.

As regards efficiency there is no rivalry between electricity and compressed air; the overall efficiency from generator to motor is about 60 %, while with compressed air it seldom attains to 15 %. In fact, Professor Hay * says that compressed air consumes *at least* five times as much energy as electricity.

834. Coal Cutters.—The use of coal cutters is to remove a layer of coal or rock at the bottom of the coal-face, the material overlying

* *Proc. Inst. C.E.*, Vol. 223, p. 200.

the cut being then brought down by suitable charges of explosives. As compared with hand mining, a machine cutter is able to work economically in much thinner seams (down to 16 or 18 ins.), and to yield a much greater tonnage from a given working face, whilst much reducing the cost per ton, though the heavy-cutting type of machine in general use in the thick American seams is seldom suitable for this country. In 1912 about 2 400 coal cutters (all types and drives) were in use in the United Kingdom; in 1926 there were 6 512, of which 3 114 or 48 % were electrically driven and the balance by compressed air; in 1931 there were 7 371, of which 4 026 or 55 % were electrically driven.

From the Report of the Electrical Inspector of Mines for 1931 the following figures are deduced:—

In Scotland 61·3 % of the total output of the mines was got by machine mining, and of that so got, 97 % by electrical cutters. In other parts the proportions are smaller, but for the whole country it appears that 20 % of the *total* output was from electric cutters, and a further 10 % machine cut by compressed air. The output per machine cutter (all types) is now about 10 000 tons per annum in the United Kingdom as against 8 000 tons before the war. It is recorded* that at Cannock Chase Colliery, an output of 15 tons per man-shift has been secured with pillar and stall working; and in Scotland a 2 ft. 6 in. seam has been cut on the same system at an overall cost of 3·69d. per ton.

As regards the arrangement of the cutting tools themselves, machine cutters may be classified as percussive or pick machines, bar, disc, and chain cutters.†

Percussive machines were, until recently, operated almost exclusively by compressed air, and their action is to chip coal in a manner similar to that employed by the miner. These machines are extravagant of air and yield only 2 500 to 3 000 tons of coal per annum; they should be used only on short faces. Longwall cutters, operating on long working faces, are much more economical; their average production is about 10 000 tons per annum per machine, and of these machines about two-thirds are driven electrically.

* 'The Times' *Engin. Rev.*, Jan. 21, 1928.

† The bar, disc, and chain cutter are compared exhaustively by Mr. Sam Mavor, 'The Applications of Machinery at the Coal Face,' *Jour. I.E.E.*, Vol. 64, p. 932 *et seq.*

In *bar*, *disc*, and *chain machines* respectively, cutting tools (removable for sharpening) are set radially in a tapering bar, radially in the rim of a horizontal disc, or in tool boxes in an endless chain. The bar cutter needs minimum starting torque, and is less liable than the disc machine to injury by falls; only about 2:1 speed reduction is required from the driving motor, as against 30 or 50:1 in disc and chain machines. Special types of chain-type cutters are useful in driving headings.

The older disc, chain, and wheel longwall machines have been brought up to date, and there are now many efficient standard types arranged for both electric and compressed air drive. A recent importation from America is the shortwall machine, capable of rapidly cutting the bords and walls in bord and pillar work. These machines seriously challenge the supremacy of the reciprocating air coal cutter, of the percussive type. Another successful challenge to the percussive air machine is the Hardy rotary cutter, which closely resembles the air machine in operation, except that the motion is rotary. It is worthy of remark that the Hardy Bedford requires $1\frac{1}{2}$ H.P. whilst the air machine requires the equivalent of 20 H.P. at the compressor for the same work (Prof. Hay).

To these may be added the arcwall machine, a further importation from America. This and the shortwall machine 'may be said to have given the pillar and stall system a new lease of life.'*

The 7 371 coal cutters in use in 1931 were of the following types:—

Disc	450
Bar	525
Chain	4 287
Percussive and other	2 109
Total	7 371

Of these, 3 345 or about 45 %, mostly of the percussive type, were operated by compressed air. Chain machines are steadily displacing the disc and bar type, and represent about 82 % of the total, *exclusive* of percussive machines, as against 60 % in 1926 and 28 % in 1916. Percussive machines, although still increasing in number annually, are not gaining over the other types proportionally. Points to be considered in deciding on the type to be used in any particular case are: speed of cutting, strength of machine, freedom from breakdown, adaptability to the conditions encountered, ease of effecting repairs and renewing cutters.

* 'The Times' *Engin. Rev.*, Jan. 21, 1928.

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Either squirrel-cage or slip-ring A.C. motors, or compound-wound D.C. motors, may be used. From 10 to 20 or 25 H.P. is usually provided. The motor is completely enclosed, and made very low so as to permit working in very thin seams; 3-phase motors of very low height are, however, sensibly less efficient than D.C. motors of the same height. Ventilation is a serious problem. Drum controllers are generally used, and arranged to be operated from either end of the machine. Longwall cutters are self-propelling, being fitted with sledge runners and a rope-and-drum gear. Current supply is taken through trailing cables (§ 820) from a gate-end box.

In some recorded tests it was found that the energy consumption lay between 0.2 and 0.3 kWh per sq. yd. undercut, and between 0.3 and 0.5 kWh per ton of coal obtained. When holing in hard material, the energy consumption may exceed 0.75 kWh per sq. yd. undercut. Messrs. Hoskin and Fraser* give the following formula for finding the H.P.-hrs. required in D.C. coal cutting:—

$$\text{H.P.-hrs.} = \text{No. of machines} \times \text{operating time (hrs.)} \times \text{kW} \times 1.34 / h \times t,$$

$$\text{or} = \text{daily tonnage} \times 0.55 \times 1.34 / 24 \times h \times t \times \text{coal thickness (ft.)},$$

where h = mechanical efficiency of engine-generator set (0.82 to 0.85);

t = transmission efficiency (0.75 to 0.95).

For A.C. it is necessary to make the additions referred to in § 824.

Tests have shown that the power consumed by a chain-type coal cutter may be trebled (60 H.P. instead of 20 H.P.) if the picks be blunt and the general maintenance of the machine be neglected.

835. Conveyors and Loaders.—The use of mechanical coal cutters has greatly increased the yield of coal at each point of use, while the workings are, for the most part, laid out for hand-mining both as regards the actual point of mining and the roads from it to the shaft. Consequently the use of conveyors is almost a necessity in these cases where intensive mining is in force, and the electrically-driven conveyor is in active competition with the pneumatic. In 1926† there were 1 667 conveyors of all classes

* See reference in § 824.

† Report of the Chief Inspector of Mines, 1926, p. 121.

in use in the U.K., an increase of 154 over the previous year. Including loaders, they accounted for over 8 000 H.P. of motors. In 1931 the number of conveyors and loaders was 4 459, of which 2 299 were electrical with over 25 000 H.P. of motors.

There are four types of conveyors in general use, namely,

- (i) the shaker or jigger ;
- (ii) the chain scraper ;
- (iii) the rubber-faced band or belt type ;
- (iv) the scoop-type scraper loader.

For the first of these pneumatic working is obviously more suitable than electrical, as the motion is reciprocating, though electrically-driven shakers are also found ; but types (ii) and (iii) are unidirectional, and are perhaps more often electrically driven than otherwise. The scraper loader* consists of a bottomless scoop of about 1 to 3 tons capacity, which is hauled to and fro along the face by an electrically-driven double-drum haulage. The motor may absorb from 30 to 130 kW, the latter being applicable to American practice. A differential friction band coupling is frequently employed, as this enables a squirrel-cage motor to be used.

The shaker conveyor is generally used on down-grades, but can be used on the level or on slight up-grades ; the two other types of conveyor are generally used for up-grade working, the band type being able to do greater duty than the other two. The use of conveyors reduces labour and breakage of coal while permitting the face to be cleared in minimum time, ready for the next cutting shift. Reliability is essential first, last and all the time.†

Gate-end loaders, also electrically driven, are often used in America in conjunction with the conveyors ; and a considerable number—506 in December, 1931—have now been put to work in collieries in the United Kingdom.

An elaborate conveyor system requires efficient traffic control. These conveyors are at a disadvantage in pits where small tubs or trams are employed, and mechanisation is gradually leading British mining engineers to attack this the weakest point in the system. Already in South Wales, where the use of conveyors has developed most rapidly, 30-cwt. trams and 40-lb. to 45-lb. rails on a 3 ft. 2 in. gauge are being employed. In America 12-yd. rails weighing 100 lb. to the yard on a 3 ft. to 4 ft. gauge are not uncommon in conjunction with locomotive haulage, which for various reasons makes slow progress in British mines.

* A valuable article on this subject is 'Scraper Loading in Durham,' *Colliery Engineering*, Vol. 8, p. 68.

† The subject is dealt with fully by Mr. Sam Mavor, *loc. cit.*

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In this country the most notable development has been in the use of a multiple or trunk conveying system, which serves to eliminate a number of gate roads and concentrate loading points. At the Taff Merthyr Colliery coal is delivered from face conveyors 90 ft. long upon shaker conveyors, which conduct it to the loading points. The classic example in this country is, however, to be found at the Newbattle Colliery in the Lothians. Among minor improvements is the use of quick adjustable connections on trunk conveyors and of means to protect belting and prevent the spillage of coal. At several collieries ball bearings are being adopted for both conveyors and screens. A comparative novelty is the employment of flexible suction conveyors at Tursdale and Bowburn Collieries in Durham, and of somewhat similar plant at the Bestwood Collieries in Notts.—'The Times' Eng. Rev., Jan. 21, 1928.

836. Drills.—Both rotary and percussive rock drills are used extensively in some mines; and, though the great majority of these are driven pneumatically, there are rotary electrical types in use. The rotary type may be driven conveniently by an electric motor (say of 1 or 2 H.P.), and percussive drills are adaptable to electric driving either by a motor and eccentric or by electromagnets (solenoids). The power consumption in drilling shot holes is about 1 kW. Where compressed air is used, owing to its value in ventilating the workings, portable motor-driven air compressors are often found. In very hard rock, electrically-driven diamond drills are sometimes used.

In a recent paper * Professor D. Hay states that he has 'recently had some success with an electric rotary drill in normal coal measure shales and sandstones, but in ironstone and very hard sandstone progress is slow with this type: *there is a wide field awaiting a good electric stone drill in collieries.*' (Our italics.) The Electric Inspector of Mines also refers to this matter:† 'A handy and compact rotary electric drill has been tried out at several collieries during the year, for putting shot-holes into the coal. It is used single-handed, the weight of the machine being 25½ lb. The 3-phase squirrel-cage motor, rated at $\frac{3}{4}$ H.P., and designed for 125 V, 50 cycles, runs at 2 800 r.p.m., and drives a hollow drill spindle through double spur gearing at 320 r.p.m. The control switch is fitted in one of the two lug handles, and a small 4-core flexible cable and connector, which carries the current to the drill from a transformer rated at 1 kW 600 / 125 V 3-phase, allows the operator freedom of movement. In actual trials at Cannock Chase Colliery, by colliery workmen, holes to a depth of 4 ft., which

* Proc. Inst. C.E., Vol. 223, p. 201.

† Report for 1926, p. 17.

necessitated a change of drills half way, were put into a strong measure at the rate of 2 ft. per minute.'

837. Miscellaneous Machines.—Both underground and on the surface electricity is used for various miscellaneous purposes, as to which separate statistics are not available. Coal washing and screening account for between 5 and 15 % of the total motor H.P. installed above-ground in the principal divisions of the country, Yorkshire having the highest percentage; and the total for coal washing and screening amounted to 166 569 H.P. in 1931. In addition, the aggregate H.P. of motors classed as 'miscellaneous' in the Report of the Electrical Inspector of Mines for that year was 19 160 below and 345 223 above-ground; or 364 383 in all. Where a coal or other mine has adopted electric working at all, most of the machinery at the surface is driven by motors as a matter of course, except where the necessity for reciprocating motion renders compressed air more suitable. There must always be repair shops attached to mines, with various machines requiring power. Haulage on the surface is, however, generally a matter of railway trucks on a siding, for which shunting engines are mostly used.

838. Shot Firing.—There are several electrical systems of shot firing, all of which are superior to older methods in safety, convenience of group firing, and absence of miss-fires. In 1931 24 million lb. of explosives were fired in 48 million shots, including 16 000 miss-fires; * fuses missed 1 in 2 690, squibs 1 in 2 340, and electricity 1 in 3 220 shots.

The detonating material of the fuse may be set off by sparking between two electrodes embedded in it, or by incandescence of a fine platinum wire similarly disposed. The spark system requires a small current at 100 to 200 V, which may be obtained from a small hand-driven magneto-generator, suitable provision being made to ensure that sufficient E.M.F. is being generated before the firing circuit is closed. Research work has been carried on at the Testing Station at Sheffield in connection with the formulation of standard tests for shot-firing magnetos. The glow system of firing requires a heavier current at lower voltage, say 3 A at 20 V, and this may be provided by a storage battery or by a low-pressure magneto-

* Report of the Chief Inspector of Mines, 1931.

generator, the latter being more convenient.* Several shots may be fired simultaneously by connecting the fuses in series or parallel. If spark fuses be connected in series, there is some risk of the most sensitive one exploding and interrupting the circuit before the others operate. On the other hand, there is no guarantee that all of a number of parallel connections are in order. Glow fuses connected in series give minimum risk of miss-fires, and this system is generally employed. Regulation 133 (a) prescribes that 'current from lighting or power circuits shall not be used for firing shots'; the 'Explosives in Coal Mines Orders' should be referred to, as to the source of electric current that may be used for this purpose. The same Regulation (b) lays down that 'shot-firing cables shall comply with Regulation 130a (§ 819) relating to flexible cables, and that adequate precautions be taken to prevent their touching other cables and apparatus.'

839. Mining Telephones and Signalling.—Regulation 122b requires that 'efficient telephonic or other equivalent means of communication shall be provided for communicating between the place in which the switchgear provided under Regulation 128a (§ 822) is erected and the shaft bottom or main distributing centre in the pit.' Actually, extensive use is made of telephones in most modern collieries; the instruments are necessarily constructed so as to be watertight and be capable of resisting very rough usage; it is desirable also that they be of the loud-speaking type, and provided with powerful battery or magneto ringing equipment. Departmental research work on the formulation of standard tests for mining telephones is in progress.

Electric bells or hooters offer a very convenient means of signalling along haulage roads, and for other purposes underground, and these with their relays are also the subject of enquiry, testing and approval. Bare conductors mounted close together, so that they can be brought into contact at any point by grasping them or by placing a piece of metal across them, have been used for such signalling circuits in the past, but this system inevitably introduces more or less risk of 'open sparking' and is held to have been responsible for at least one serious disaster. Regulation 134 prescribes:—

(a) Where electricity is used for signalling, the pressure in any one circuit shall not exceed 25 V. (b) Contact-makers shall be so constructed as to prevent the

accidental closing of the circuit. (c) Adequate precautions shall be taken to prevent signal and telephone wires from touching cables and other apparatus.

These rules are obviously of limited scope, and the onus of determining when 'open sparking' becomes dangerous is left to the colliery manager. Mr. C. P. Sparks suggests that the following systems ensure safety:—

(A) *For Signalling over Moderate Distances.*—Circuit wires to be of bare galvanised iron, 8 S.W.G., and placed high up on insulators on opposite sides of the road. Bells to have the contact-maker completely enclosed in a flame-tight metal cover, and the magnet windings shunted by a non-inductive resistance of suitable value. The number of dry cells to be limited to ten (*i.e.* 15 V), the battery being divided into two halves, one connected near the bell, the other half-way along the line. The batteries to be kept in locked boxes capable of accommodating only the standard number of cells, so that exhausted cells must be replaced instead of an indefinite number of cells being added in series. Signals to be made by switches operated by a pull-wire, the switches being enclosed in flame-tight metal cases and breaking contact through non-inductive resistances mounted in the same cases.

(B) *For Long-distance Signalling.*—A high-resistance relay with shunted contact and enclosed in a flame-tight metal case should be used, the shunt resistance being placed inside the case. The line pressure can then be kept down to 6 V. Alternatively, the A.C. system should be adopted, the same system of wiring and switches being used as under (A). Battery maintenance is then eliminated. The transformer pressure should be 15 V, and the bell coils should be enclosed in rigid metal.

Signalling by make-and-break between bare conductors cannot be regarded as safe practice in any place where there is liable to be explosive gas or coal dust. The circuit pressure must be so low that an arc cannot be started; but this is not the only, or even the most, important factor. It is the amount of electromagnetic energy stored in the circuit to be broken, and the rate at which this energy is dissipated, which determine the temperature of the spark. The inductance of the bell magnet windings is therefore an important factor, and these windings should be shunted by a non-inductive resistance, to prevent their stored energy being dissipated at the switch contacts, to the detriment of the latter. Even so, there is a risk of dangerous sparking if the signalling contacts be 'open.' Enclosed switches situated at intervals along the road, and operated by pull-wires, permit signalling from any point, whilst eliminating the objectionable features of the older system.

Several successful systems of *shaft-signalling* have been devised to comply with Regulation 95, which requires that 'in connection with every winding engine there shall be provided an appliance indicating automatically and visibly to the winding engineman (in addition to the ordinary signal) the nature of the signal until the

signal is complied with.' It is further required that the banksman be able to signal to the winding engineman and to the onsetters, and also to receive signals from the onsetters. The signalling equipment may be purely electrical or electro-mechanical in nature. Details vary in the several systems, but generally a series of tappers are used to send signals, which are received and indicated by an apparatus resembling a ship's telegraph. Checking signals are reproduced at the signalling point, the engine-driver is given bell or hooter signals (or both), and a pointer moves round to the appropriate section of the dial, which is illuminated to show the level from which the signal is sent. The audible signal is coded, and the illuminated portion of the dial shows the order in words as well. The visible signal is shown until it has been obeyed, and arrangements are made to prevent interference with or confusion between signals.

840. Electric Lighting in Collieries.—Whatever future developments may be, underground workings are now generally illuminated only by portable 'safety' lamps, except in the case of main roads, underground workshops and motor-rooms, etc., where ordinary glow lamps with carbon or metal filaments may be (but seldom are) used, so long as the lamp-holders, conduit, switch and fuse boxes are earthed when required by Regulation 125 (§ 821), and so long as Regulation 132 (iv) (§ 812) is observed. It is likely that the future will see more extensive fixed lighting in the workings, as this must obviously tend to saving of time and health and lead to greater efficiency. The reason given to one of the authors (Mr. Meares) why a certain well-known Mysore gold mine had unlighted roads—namely, that if the cracked and groaning timber supports were rendered visible no one would go down—does not apply in Great Britain, where regulation and inspection are very thorough. Professor Hay * mentions as a present-day consideration that special lamps are now obtainable which can give good illumination horizontally, as needed for this work. For wiring, small sized armoured cables are largely used, with iron-clad fittings filled solid. (Electric lighting generally is treated in Chapter 25, Vol. 2.)

841. Safety Lamps.—Regulation 122*a* demands that, wherever failure of electric light would be likely to cause danger, one

**Loc. cit.*

or more safety lamps or other proper lights be kept burning continuously. The oil-burning Davy 'safety' lamp which, in one of its many modifications, was used exclusively for so many years, has now to meet keen competition from electric safety lamps. Between 1912 and 1931 the number of electric safety lamps in use in Great Britain increased from 11 000 to 387 000, while the number of oil lamps has decreased since 1920 from 640 000 to 337 000. By far the greater number of the oil lamps are re-lighted electrically, and nearly half of them are sealed magnetically.

Electric safety lamps must be of a pattern approved by the Home Office,* and rigid requirements are imposed which have undoubtedly retarded the introduction of the new lamps, whilst being all in favour of enhanced safety and technical merit. One requirement is that an electric miner's lamp must give at least 1 spherical c.-p. after 9 hrs. continuous burning; this corresponds to much better lighting than is given by oil safety lamps, and the use of the electric type is found to reduce materially the prevalence of nystagmus among miners. One advantage admitted for the oil lamp is that its 'gas-cap' gives timely warning of the presence of dangerous quantities of inflammable gas. This is an important point, and various arrangements have been devised to provide a similar warning where electric lamps are used. One method is to use an electrically lighted auxiliary Davy lamp; another employs the change in electrical resistance of a special wire, when exposed to firedamp, to vary the deflection of a small galvanometer built inside the lamp glass and calibrated in 'per cent. of gas present.' Yet another form of gas-detector depends on diffusion through a porous plate changing the reading of a manometer which is calibrated to indicate the corresponding percentage of gas.

The general requirements to be fulfilled by any electric miner's lamp are that there should be no open sparking at the key or switch; that fracture of the guard glass surrounding the lamp bulb should at once extinguish the lamp (for even a miniature tungsten lamp may ignite a gaseous mixture if the bulb be broken whilst the filament is incandescent); and that the battery container be able to resist very rough treatment. The lamp may be

* The types of safety lamp approved by the Mines Department from time to time, under the Coal Mines Acts, are described in the Statutory Rules and Orders issued by that Department, and are obtainable from H.M. Stationery Office.

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locked by a lead seal or by a magnetic bolt which can only be released by aid of a strong electromagnet. Either lead or nickel accumulators (Chapter 18) may be used, and it is very important to ensure that no electrolyte can be spilled inside the lamp casing, also that 'creeping' and corrosion do not occur. Lamp renewals and battery maintenance represent the chief items of expenditure. Tungsten filament lamps are of course employed, these yielding about four times the candle-power-hours of lighting obtainable by carbon lamps from the same battery, or alternatively reducing the weight of battery to be carried for given lighting service. It should be remembered that even a decimal part of 1 V corresponds to considerable variation in life and candle-power of a 2 or 2½ V lamp; hence it is worth while determining carefully the mean P.D. of the battery during the normal discharge period, and then selecting the lamp to suit this pressure. In recent years a great increase has taken place in the number of alkaline lamps in use, 27 000 being in service at the end of 1931, compared with 23 000 at the beginning of that year. Four-volt lead-acid lamps are also being used much more extensively, but no precise figures are available. Both frosted and tinted and lens-shaped glasses have been tried for obviating glare and concentrating the light, as well as multiple vertical internal prisms. Cleanliness and observance of a regular charging and maintenance schedule, coupled with intelligent observation of irregularities in behaviour, are the secrets of low battery costs. Expenditure on a well-equipped charging-rack and cleaning equipment, and organisation of an effective system of inspection and records, is well invested. Detailed descriptions of electric lamps for miners and of lamp-room equipment are to be found in technical periodicals, and of the former in the official Orders approving the lamps. Large users of miners' electric lamps give the total cost of the latter (including wages, maintenance, and capital charges) variously as ½d. per shift; 3½d. per week; and 'twice as dear as oil lamps.' These estimates are more or less consistent, and the important points are that the cost of the electric lamps is quite moderate; the light obtained is three times that given by oil lamps; and the resulting improvements in working safety and efficiency far outweigh the higher cost of the light itself.

842. Mines and Quarries other than Coal Mines.—The preceding paragraphs of this chapter, though of general applica-

tion, have referred more particularly to collieries, as these represent by far the greater part of the mines of this country and have their own special problems due to the ever-present risk of explosion.

Electrical working is, however, extensively used and rapidly expanding in the metalliferous mines and quarries. The Chief Inspector of Mines gives the following table* relating to mines employing electricity:—

TABLE 178.—*Use of Electricity in Metalliferous Mines.*

	H. P. of Electric Motors Installed.	
	1926.	1931.
<i>Above-ground.</i>		
Winding or hoisting	2 113	3 930
Ventilation	909	709
Haulage	798	932
Pumping	911	834
Dressing or cleaning	3 326	3 924
Other purposes	6 166	9 885
Total above-ground	14 223	19 714
<i>Under-ground.</i>		
Hoisting	617	598
Haulage	947	1 349
Pumping	7 657	8 748
Other purposes	1 003	1 220
Total under-ground	10 224	11 915
Total above and below-ground	24 447	31 629
No. of mines using electricity	74	83

These mining operations include iron, lead, tin, zinc, and manganese, along with various minerals used in the chemical industries, in smelting, in building, and in road making.

In other countries electricity is used in every sort of mine

* Reports for 1926 and 1931. See also 'Electricity in Mines,' by R. Nelson, *Jour. I.E.E.*, Vol. 64, p. 1014.

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and mining operation, especially where water-power is available. Thus, in India, the Kolar goldfields gave rise to one of the earliest hydro-electric schemes, employing a long transmission line, namely, from the Cauvery Falls to Sivasamudram; some 30 000 H.P. is installed, mainly on the surface, for air compressors, stamps, rolls, tube mills, sorting, etc. The electrical equipment of the rock-salt mines in the Punjab, for disc cutters, haulage, screening, creepers, pumping, and lighting, has also been undertaken. In Burma the oilfields, the Ruby Mines of Mogok, the complex silver ore mines near the Mansan Falla and the Wolfram mines of Tavoy have their several steam or hydro-electric plants for similar services, as well as for hydraulic mining and sluicing and pumping.

The last-named method, also known as hydraulicizing—the use of high-pressure water instead of faith for ‘removing mountains’—is of course carried out by means of natural pressure due to the head on a pipe-line when conditions allow this; but in other cases the pressure is obtained by pumping, and often electric pumping.* Gravel pumping is another special application, used in the tin mines of Malay (and elsewhere) where it is recorded† that the impellers and liners last from 10 to 14 days when pumping up to 6 % of solid matter. Electrical dredging was used for channel clearance in Kashmir twenty years ago and is used for tin (and other) mining now. The power is sometimes taken to the dredger on barrel floats—a novel form of transmission—6 to 10 ft. apart (Sparks, *loc. cit.*). The annual load factor is said to be about 65 %, and the daily load factor may reach 85 %. The following particulars of such a dredger (*loc. cit.*) of smaller size than is likely to be used in the future, are of interest :—

Capacity 150 000 cu. yds. per month from a depth of about 60 ft.

Buckets, 7 cu. ft. each.

Max. demand, 260 kW.

Equipment, Transformer 3-phase, 50 cycles, stepping down to 415 V.

Digging motor,	150 B.H.P. with belt, friction, clutch, and reduction gear.
Classifier pumps,	75 "
Pressure water pumps,	130 "
Ladder hoist,	60 "

*The ‘Hydrautomat’ (§ 280, Vol. 1) is in use for this purpose and for air compression in Nigeria.

† ‘Some Impressions of Mining in the Federated Malay States,’ A. C. Sparks, in a paper read before the Association of Mining Electrical Engineers, Jan., 1928.

Winch,	25 B.H.P.
Screens,	35 "
Tip,	25 "
Cable drum,	3 "
Bilge pump,	2 "
Auxiliary winch,	10 "

In tin and other metalliferous mines, and also (as mentioned in § 809) in the mining of various precious stones, the use of magnetic separators is considerable; not only for removing iron, but for any material having even faint magnetic properties.

In the mine of the Utah Copper Co. (U.S.A.) electric shovels,* with caterpillar tractors, have completely superseded the steam shovels previously used, the cost of working the former being only 37 % of that of the latter. They have $4\frac{1}{2}$ cu. yd. dippers and are operated partly by D.C. motors with Ward-Leonard (§ 716) control and partly by A.C. motors.

The Report of H.M. Electrical Inspector of Mines shows that electric motors were installed at 852 quarries, including clay, sand and gravel pits, in 1931; the total capacity of these motors was 114 145 H.P. of which about 75 % was A.C., 21 % D.C., and 4 % mixed.

The cutting of slate and stone and the crushing and grading of quarry products and, in fact, every conceivable mechanical operation in and about mines and quarries employ electricity now and will employ it to a far greater extent as electric power becomes cheaper and spreads its transmission tentacles further afield. The considerations in the coal mining paragraphs of this Chapter apply, *mutatis mutandis*, to all classes of mine, with the very important proviso that, where neither gas nor explosive dust are present, many of the precautions essential in coal mines can be relaxed or entirely abrogated.

843. Bibliography.—(See explanatory notes, § 58, Vol. 1.)

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* *Mining Congress Journal*, Sept., 1927, p. 674.

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- No. 227.—Steel Arches for Use in Mines (Straight-sided and Horse-shoe Arches).
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- No. 236.—Flattened Strand Steel Wire Ropes for Colliery Winding Purposes.
- No. 237.—Flattened Strand Steel Wire Ropes for Colliery Haulage Purposes.
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CHAPTER 33.

ELECTRICITY IN AGRICULTURE.

844. Introductory.—The two greatest industries in this country, one below-ground and the other on its surface, once flourishing and always vital, have now for some time been in the throes of acute depression. ‘Agriculture is by far the most important industry within the British Empire; even in England and Wales, with its urban conditions, the annual agricultural output reaches the figure of £225 000 000.’* The unbiassed observer is apt to wonder whether the entry into politics of coal mining and agricultural questions has not some direct connection with the present deplorable condition of these basic industries; but he is quite sure that failure to move with the times has had an even more direct effect. Why otherwise should home farm produce be always far more expensive than that from the Dominions and abroad, while the farmer complains that he can barely make a living? No such complaint comes from Scandinavia, where there is co-operation both in marketing and in power appliances. In view of the shortage of agricultural labourers, due to the rush to the colours during the war, and the drift to the towns and their factories both then and since, mechanisation is essential; it began long ago in our parallel instance of coal mining (*see* Chap. 22), and has at any rate helped ‘to keep the home fires burning’; but the farmer is even less inclined to change his ways than the coal owner in order to keep the home farm running. Furthermore, the farmer generally lacks the capital† necessary for installing modern methods,

* Report of the Imperial Agricultural Research Conference, 1927. (H.M. Stationery Office.)

† The situation in this respect has been considerably eased by the arrangement of loans at a low rate of interest. Farmers can borrow money more cheaply than anyone else, provided the scheme for which the loan is desired is approved by the Ministry of Agriculture. Many farmers are unaware of these facilities, by taking advantage of which they should be able to increase their prosperity, repay the loan and secure a margin of profit.

because holdings are small and he seems unwilling to co-operate with his neighbours except possibly over a cider press.

From the labourer's point of view also, the long hours in all weathers, the isolation, and the lack of all the amenities of the town (except 'wireless') for his family have not been counter-balanced by the great rise in pay during the last thirty, and especially the last ten, years. His companion, the farm horse, has no such freedom to choose where he will work; and, along with the pit pony, continues to do work that can be done far better and cheaper by means of electrical horse-power. However, it is comforting to think that the elephant has at last disappeared in warfare, after an innings stretching from the era of Hannibal to that of Kipling, and that the horse is following; for mechanisation is rightly taking its place both in war and in peace, and modern plant objects neither to overtime nor overload. It is a significant fact that in America there were about 35 acres in crops per agricultural worker in 1920 against 18 acres in 1870, while the power used in agriculture has risen between the same dates from $1\frac{1}{2}$ H.P. to 4 H.P. per worker, *i.e.* the acreage per man increased in nearly the same ratio as the power employed.

In this chapter the uses and advantages of electricity in agriculture are briefly considered; and, to save the tedium of a complimentary reference on almost every page, a tribute to the work of Mr. R. Borlase Matthews, Wh.Ex., M.I.E.E., etc., may be paid here. Mr. Willett, who first proposed 'summer time'—now adopted by all save the cow—and who was laughed at by the whole world as a visionary and an enthusiast, was proved a true prophet during the war. Mr. Matthews,* equally an enthusiast, is having a harder task; for when once the war ended, and the obvious necessity for 'speeding the plough' mechanically lapsed, along with millions of acres of arable land, the lesson of our dependence on foreign produce was forgotten. Incidentally, the absence of any power supply in rural areas has militated against the use of electricity; but the fact that the provision of this supply is one of the planks of the edifice now being built up by the Central Electricity Board is worth pondering over.

Except for hedging and ditching and thatching, there are few

* The authors' thanks are due to Mr. Matthews for reading the MSS. of this chapter and making many useful suggestions thereon at the time when his own volume on the subject (*see Bibliography*, § 861) was just being issued.

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things done on a farm by man or beast that cannot be better done by power; and there are also but few things done by direct steam- or oil-engine power that cannot be better done by electricity. Agriculture is, of all industries, the one requiring in the aggregate the most power—more, in fact, than all other industries put together,* and there is no inherent reason why nearly all that is now provided manually and by animals should not be furnished electrically. The cost of cultivation can be reduced by applying mechanically a higher power than animals can exert, thus doing the work more quickly and saving the time of labourers; and, apart from this direct saving, it is important to be able to get through the work quickly when the weather is favourable, as in ploughing—the heaviest work on a farm—or thrashing. Power is needed over such large areas that the convenience and economy of electricity used in individual driving is here shown in a most marked degree; and it is the only form in which it can be economically transmitted under farm conditions, as an alternative to portable prime movers.

The problem of substituting mechanical for manual labour on the land is acute in every industrial country, as well as in many of the lands which serve to feed the former, because of the shortage and high cost of labour for manual tasks on the land. By increasing the amenities, power may be of real assistance in the 'back to the land' movement.

For descriptions and illustrations of various electrical appliances for the farm, exhibited at the Paris Agricultural Exhibition of 1928, the reader is referred to Mr. Matthew's summary in the *Electrical Review*, Vol. 102, pp. 364, 455. Footnote references have been given, as usual, throughout this chapter to the authorities quoted, chief of whom is Mr. Matthews, who has not only been the pioneer worker in this field in this country, but has also visited, examined and described what has been done abroad.

845. Power Supply for Agriculture.—In Volume I, Chapters 4 to 10, the generation of power has been dealt with at length, with comparisons of the various prime movers—steam, oil, wind and water—and the various systems—D.C. and A.C., high and low pressure, single-phase and three-phase. Here it is only necessary to consider the specific problem of supplying power to

* R. Borlase Matthews, *El. Rev.*, Vol. 99, p. 132.

the farm. The possibilities are enormous, and some of the calculations referred to presently appear fantastic; but there has been but little exploitation so far. The problems are new, and demand new organisations and methods, because the basic conditions are different from those in other industries in densely populated areas. The loads are scattered and the distances long; conservatism, inertia and the lack of standard equipment have militated against the tackling of such a new order.

It is clear from the lack of progress hitherto that agriculturists are not prepared to incur the expenditure involved in laying down private generating plant; the industry is not in a position to find the capital,* so it is useless to discuss it in detail. If, however, a stream runs through the land, and has any reasonable fall (from 3 ft. upwards) between the points where it enters and leaves the estate,† the possibility of concentrating that fall at one point for the generation of energy is worthy of investigation. True, the capital expenditure involved may prove to be prohibitive, but if, on the other hand, it should prove reasonable, the subsequent cost of power will probably be lower than can be obtained from any other source. For the possibilities and assessment of water power the reader is referred to Chapters 8 to 10. In the absence of water power capable of cheap development, the farmer must look to the 'cheap and abundant supply' promised by the State, and now in process of development by the Central Electricity Board (§ 1041). An abundant supply can certainly be guaranteed; but in calling for a cheap supply we may find ourselves in the position of being able 'to call spirits from the vasty deep.' Great savings in generation will be made; but enormous expenditure on the transmission lines of the national 'grid,' and on rural lines radiating from these (for which no provision is made in the Electricity Supply Act, 1926) will have to be paid for somehow. There should, however, be a more equal incidence of the cost of supply and an appreciable diminution in overall cost as the load factor rises; and supply will be available where at present it is not.

* See, however, footnote § 844.

† In the Report of the Departmental Committee on Agricultural Machinery (Ministry of Agriculture) mention is made of the large number of readily developed water powers going to waste, especially in Wales; and the authors can confirm this. Where used at all, an inefficient water-wheel is used instead of a modern turbine.

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The national 'grid' primary supply is 3-phase A.C., at 132 kV, 50 cycles, but this E.H.T. supply must be transformed down to ordinary high pressure—3 000 V, 6 000 V, or perhaps 11 000 V—for the network which will actually feed the consumers, at 400 V for 3-phase motors and 230 V for lighting and small single-phase motors; and from the feeding point the matter is dealt with in the next paragraph. As an index of practice elsewhere, it may be mentioned that the rural networks in Wisconsin—where electro-farming has gone ahead—are on the following lines:—

Primary.—Single-phase, 5 000 V, on 30 ft. poles with 7 in. tops, 300 ft. apart, with No. 2 Am.W.G. aluminium-covered steel wires. Every tenth pole is anchored, and 20 ft. clearance is allowed above-ground. The cost of the line (exclusive of transformers, arrestors, etc.) is about £150 per mile.

Secondary.—240 / 120 V single-phase, 3-wire, on 30 ft. poles, with 6 in. tops (except for those carrying transformers, which have 7 in. tops), 150 ft. spans, using No. 6 Am.W.G. copper wires.

At the present day A.C. is the best system from the consumer's point of view. He can transform down to an absolutely safe voltage for use in farm buildings and houses, while transmitting at whatever higher pressure the distances demand to points where field work is to be done. For every purpose A.C. is satisfactory, and its only disadvantage is that batteries for reserve power cannot be charged without the use of a rectifier; but as there is little prospect of any farmer desiring to spend money on a battery, this may be left out of account. A man or a horse, however, will go sick far more often than a modern motor.

It will, unfortunately, be a good many years before supply from rural lines connected with the 'grid' will be generally available everywhere; * and, even when it is, service lines of a length unknown in town supply will often be necessary. The cost of these is a very serious item, whether initially borne by supplier or consumer, and the latter has, directly or indirectly, to pay for them. Just as it may often pay a farmer to sink his own well, rather than pay for miles of mains, so it may pay him to set up his own—or his co-operative—generating plant, if he has the capital (see § 859 on 'Ways and Means').

* An excellent 'Electricity Supply Map of Great Britain' was issued as a supplement to *Electrical Industries*, Nov. 9, 1932. It reveals clearly the vast amount of work to be done before anything like general supply is available in agricultural districts.

846. Transmission by Rural Lines.—In the preceding paragraph it is assumed that 3-phase power at some moderate high pressure (3 000 to 6 000 V) is available in the neighbourhood of the farmer from the network of the supply authority; then that authority, on demand, would run a service line at the same high pressure to the estate. It is abundantly clear that the farmer's business will begin and end on his own land, so that the question of transmission thither need not be discussed here; the transmission of power and its control are dealt with fully in Volume 1, Chapters 13 to 16, and the transformation and conversion of energy in Volume 2, Chapter 17.

For the comparatively light loads to be expected on a farm—and even these seasonal, and often non-existent for long periods—coupled with the relatively long distances to be served in agriculture, it is essential to use overhead lines right up to the point of application of the power; underground cables would be prohibitive in cost, as also would even overhead lines of the only nature allowed in this country until quite recently. Even the smallest E.H.T. cable costs from £400 to £500 per mile installed. A 2-wire single-phase overhead line costs about half as much as a corresponding cable, and a 1-wire line (with earth return, as suggested later) about one-third as much as a cable; and further economies will be possible under the revised Regulations. In a Memorandum* the Electricity Commissioners call attention to the disparity of cost between overhead lines and underground cables:—

For example, the cost per mile of a medium voltage (400 / 230 V) overhead distributing main ranges from £400 to £800 according to the size of conductor used, and hence the amount of energy which can be transmitted. On the other hand, the cost per mile in the case of corresponding underground cables ranges between £1 300 and £1 850. For high-tension transmission, say, at 11 000 V, the cost per mile for overhead lines would range from £500 to £900 according to the size of the conductor, as compared with a range of from £2 600 to £2 700 for corresponding underground mains.

The Memorandum goes on to deal on common-sense lines with such questions as wayleaves, pole rentals, and obstructive or dilatory behaviour on the part of local authorities. It should be read *in extenso*. The excess of caution that has hitherto always characterised the Government Department concerned with electric supply has, more than anything else, delayed progress in the United

* 'Electrical Development in Rural Areas' (1927), obtainable from the Commissioners free.

Kingdom; and it is only in recent years that antiquated Regulations have come under review in consequence of the appointment of the Electricity Commissioners, coupled with the direct pressure of the 'Overhead Lines Association,' articles in the technical Press, and the implications of the 'Weir Report' (§ 1041). New Regulations, issued in April, 1928, and further revised in 1931,* are in the right direction, though they have been much criticised in the technical Press for inadequacy. These rural lines must be cheap as well as abundant if use is to be made of them in agriculture. Even in some towns—especially in the Dominions and India—the load is so scattered that most of the cost of energy is accounted for by distribution; and with farming there will not be, on the average, more than one consumer to about 100 acres, or, say, three farms per mile and six houses per route mile of distribution. Furthermore, the individual load factors will be low, until it has been possible to carry out some educational and demonstration work for the benefit both of the engineers and the agriculturists; and in any one district the diversity factor will evidently be poor, seeing that most farmers will want to perform the same operation at about the same time. In most industries loads are reasonably constant both in amount and location, but agricultural operations are essentially seasonal, distributed over a wide area, and variable from year to year. Cheap overhead construction is essential,† and portable substations must be used to supply loads which may exist only for a day or two at a time in any particular field. The data in Table 179 are the 'weighted' averages obtained from tests on five rural lines in Wisconsin,‡ ranging from 0·57 to 4·93 miles in length, with from 6 to 26 consumers per line, the supply being single-phase at 5 000 V, reduced to 240 / 120 V, 3-wire, by pole-type transformers.

Amongst further causes that have notoriously militated against

* El. C. 53 and Memorandum El. C., 53 A and B, and El. C. 53 (Revised).

† An important development in this direction has been achieved in the mid-Cheshire district, where overhead bulk supply at 33 000 V, 3-phase, is reduced to 6 600 or 3 300 V for overhead branch lines and to 380 / 220 V for underground distributors in towns and villages. Outdoor transformers and high voltage switch-gear are employed. The cost of tapping the 33 000 V mains is said to be £75, excluding transformers, while the cost of village substations is about £250. (*El. Rev.*, Vol. 99, p. 334.) See also note, p. 524.

‡ 'Feature of a Successful Plan for Rural Electrification,' by G. G. Post (*Jour. Am. I.E.E.*, May, 1926, p. 420).

the extended use of overhead lines here are wayleave difficulties and costs and guarding requirements; while insistence on a very small range of permissible variation in voltage has hindered all electrical progress.* Guard wires are, more often than not, the cause of greater danger than that of the circuits they guard; and though in towns some earthing device for a broken overhead wire is

TABLE 179.—*Average Transformer and Consumer.
Data for certain Rural Lines.*

Number of consumers per mile of line	6
Average size of farms served	66 acres
Average load applied for when service was requested	5.59 kW
Average load connected when supply was begun	5.11 kW
Average load connected at time of these tests:—	
	kW
Lighting	0.80
Cooking	4.20
Laundry	0.67
Pumping	0.76
Cream separating	0.03
Miscellaneous	0.42
	Total ———
	6.88 kW
Average consumption per consumer per annum	1 046 units (kWh)
Average transformer capacity	5.24 kVA
Average maximum demand (15 min.) on transformer	2.63 kVA
Average transformer demand factor (= M.D. / connected load)	0.23
Maximum demand (15 min.) on line	9.6 kW
Power factor of line at time of maximum demand	0.94
Demand factor of line (= M.D. / connected load)	0.109
Diversity factor = maximum demand of line / sum of trans- former maximum demands	0.48
Losses in lines, transformers, and meters (= line input — sum of meter readings)	28.6 %

necessary, in the open country the ordinary guard wire is superfluous. The new overhead wire Regulations (*see* preceding footnote) have abolished the necessity for guard wires in most cases.

The supply of power to any given estate will, as in the case of other consumers, be delivered and measured at one point—generally near the house or farm buildings. From thence the

* The Electricity Commissioners are prepared, under their Regulations for ensuring a proper and sufficient supply (§ 1041) to allow in special cases a voltage variation within the limits of plus 4 and minus 8 % of the declared voltage on rural lines, for a provisional period pending the completion of the distribution system and its full measure of interconnection; *see* their Explanatory Memorandum El. C. 53A.

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consumer will have to make his own arrangements. Assuming (as we safely may) a high-pressure, 3-phase supply from the mains, there will probably be a pole-type, outdoor substation (§ 381) with the minimum of gear; mainly an air-break, high-tension switch of the horn arrestor type and a pole-type transformer* with tapplings for such voltages as may be required.

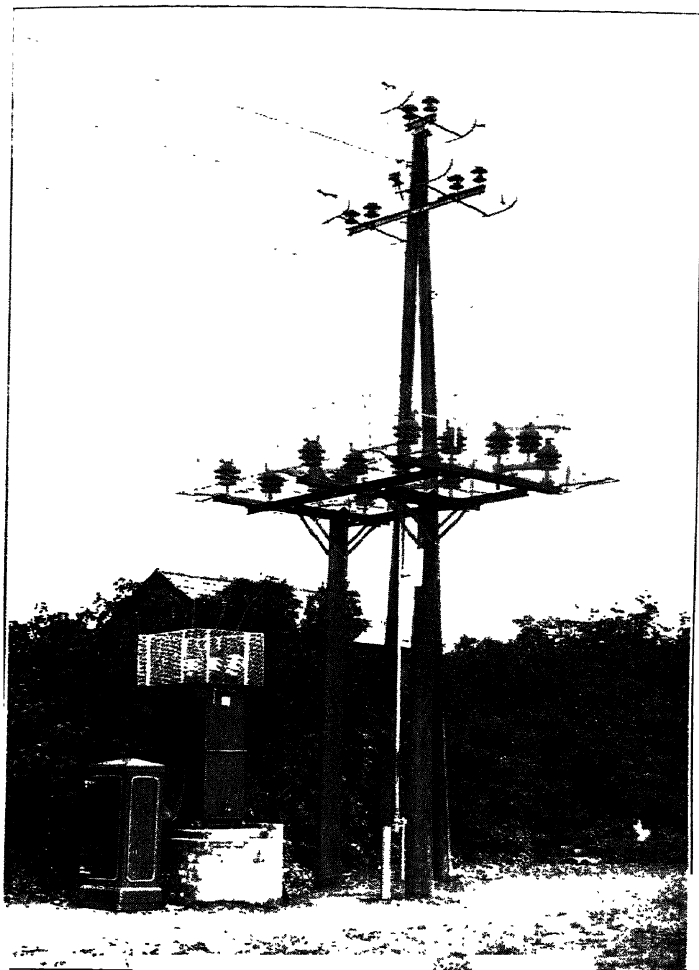
Fig. 392 shows a typical 'Metrovick' outdoor 3-phase substation of the Northwich Electric Supply Co., equipped with a 25 kVA, 33 000 / 415 V, 4-wire transformer, controlled by a 33 000 V, 3-pole combination.

Fig. 393 shows a similar substation of the same make belonging to the Chester Corporation, with a 50 kVA, 6 600 / 400 V, 4-wire transformer controlled by a 6 600 V, 3-pole farm line combination. In this, outdoor isolators connect the underground and overhead cables.

If the estate is large, further overhead lines will be run by the consumer to various points, probably in the form of a complete low-tension 'ring main' of bare wire carried on wooden poles fixed in the hedges. So long as there is sufficient clearance at gates for a loaded hay cart, and over the hedges for a huntsman with a good mount, there is no need for the 20 ft. minimum of the old Regulations, and the new code (footnote *supra*) recognises this. It would appear quite sufficient to allow 12 ft. minimum clearance above ground, except when passing gates, and 6 ft. above buildings. With short spans—the poles being obtained usually from the estate—a clearance of 16 ins. between wires would generally be sufficient.

Poles for overhead lines are dealt with in § 323, Vol. 1, and the preservative processes for wooden poles in § 86, Vol. 1; but the latter reference may be supplemented by mention of the so-called 'Cobra process,' which can be used either on cut poles or on growing timber, such as spruce, previous to cutting. A portable tool like a pole-axe is struck into the wood, and from injector holes near the point the preservative paste is forced in (by a 'grease-gun' type of piston) and left to spread evenly throughout the timber. The paste is 15 % of sodium dinitro phenate and

* Mr. Matthews considers 50 kVA as about the smallest size of transformer economically suitable on a 380 / 220 V or 400 / 230 V system. On a 3 000 / 220 / 127 V system for direct individual supply over a 600 yard radius he considered that smaller transformers can be used with economical results.



Metropolitan-Vickers Electrical Co., Ltd.

FIG. 392.—Typical 3-phase outdoor substation with 25 kVA, 33 000 / 415 V, 4-wire transformer, controlled by 33 000 V, 3-pole combination.

[To face page 490.]

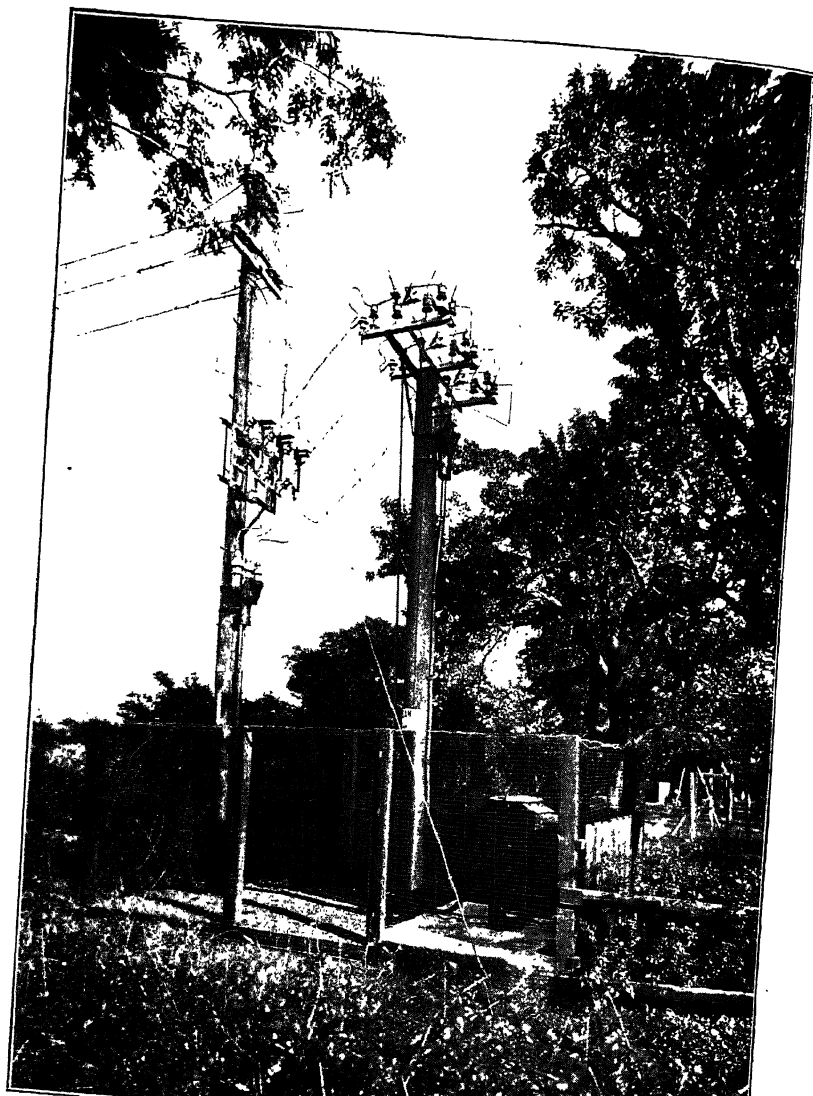


FIG. 393.—Typical 3-phase outdoor substation with 50 kVA, 6 600 / 400 V, 4-wire transformer,
controlled by 6 600 V, 3-pole farm line combination.

Metropolitan-Vickers Electrical Co., Ltd.

85 % sodium fluoride; and afterwards 'celoyd'—composed of creosote, naphthylamine and dinitro-chlorbenzole—is brushed over externally. This process seems particularly well adapted for farm lines, where suitable coniferous trees are often available. Young oak trees are very suitable for farm lines, as they need no preservative other than tarring the part in the ground and one foot above. Alternatively ferro-concrete footings or post-carriers are rapidly coming into use, one French firm having supplied over 200 000 of them.

It is open to the farmer to use his power in any form he chooses, subject to such Regulations as may be in force. The choice will generally lie between 3-phase and single-phase A.C. at various pressures; for he will certainly not install rotaries or rectifiers, and he would not be wise to do so. The 3-phase motor still has a distinct advantage over the single-phase (for motors, *see* Chapters 28 to 30), but single-phase gives simpler distribution. The acme of simplicity would be reached by single-phase distribution with one overhead wire only, using an earth return (§ 903). Such a system is not at present allowable in this country, but it appears to be technically satisfactory (except possibly for telephone interference difficulties) and is in use abroad. The cost of distribution mains will in any case be so high in proportion to the use made of them, and the revenue obtained from them, with only seasonal loads at considerable distance from the point of supply, that cheap construction is imperative.*

847. Distribution from Rural Lines.—Having a supply up to the main buildings, and branch overhead lines to the best strategic points on the farm, the next question is that of distribution (*a*) in buildings, and (*b*) on the land.

In Buildings.—For internal installation work generally, Part V. (Vol. 2) should be referred to. Of the systems of wiring described in Chapter 23 in that Part, all are available; but preference should perhaps be given to metal-enclosed or metal-sheathed systems (except of course in byres or stables), because of the possibility of a short-circuit causing a fire. These

* W. Fennell (*El. Rev.*, Vol. 95, p. 564) recommends for branch lines, carrying up to 40 kVA at 3 000 or 6 000 V: 34 ft. poles, 7½ ins. diam. at 5 ft. from the butt, planted 5 ft., with 240 ft. spans and single No. 7 S.W.G. copper with earth return; costing about £145 per mile. The same, with two-wire circuit, he estimates to cost £245 per mile.

systems are, however, expensive compared with the 'C.T.S.' or 'tough rubber-sheathed' system (§§ 551, 565), which is the most easily installed and has proved both safe and reliable. Furthermore, this wire can be used with advantage for flexible connection to any portable electrical apparatus about the farm house or buildings, from plug sockets suitably placed. It is suggested that the sockets should have covers attached to them for protecting the terminals when not in use—indeed this would be advantageous everywhere, and a falling spring flap cover could easily be attached. Mr. Borlase Matthews* recommends running the wiring of the building on the outside walls, under the eaves, and tapping this where required; or, alternatively, the use of bare wire on insulators rather than insulated cables, to serve as a ring main around the buildings, as then it is easier to tap at any point, and the first cost of installation is low. (For data as to probable consumption, see § 858.)

On the Land.—It will depend on the acreage in question whether the private overhead lines on the farm itself are low-tension or high-tension. If any pressure higher than about 550 V is used, it will be necessary to transform down to (probably) 500 V where the power is used. For this purpose a portable substation will naturally be used, the transformer being carried on a truck, with such simple switchgear as may be necessary, taken by a tractor or horse to the point of use. From this point, or from the lines themselves if they are low-pressure, flexible cables will be used to connect up any field machinery to the overhead lines. The plain rod, with a hook to hitch over the nearest point of the line, though often found abroad, is only suitable for low-pressure lines, if even for these. For any pressure not safe to handle, some secure method of tapping is essential. Several devices in use are described by one of the Authors† for tapping high-tension lines by means of sockets in such a way that the plug can neither be inserted nor withdrawn while the socket is alive.

The connection is brought down from the line by a flexible cable, as stated above, and for long lengths of this a suitable drum is usually employed, on which the cable can be re-wound after use without kinking. The type of flexible (§§ 284, 285) will of course

* *El. Rev.*, Vol. 93, p. 435.

† *R. E. Neale, El. Rev.*, Vol. 87, p. 507.

depend on the line pressure and the current to be carried. On most farms, one overhead supply line through the centre of the arable portion will usually suffice; in the case even of large farms, it will generally be found that two such lines will be enough, one along each of the two major axes of the arable land.

848. Electric Lighting and Domestic Power in the Farm Buildings.—For electric lighting, Chapter 25, and for electric heating, cooking, etc., Chapter 26 of Volume 2 may be consulted. Except for the fact that the absence of neighbours makes other amenities more desirable, the farm house is in much the same position as any other house of similar size in a town. Good lighting is always desirable; and once electricity is installed, the question of electric cooking and water heating come up, because by their means it may be possible to improve the load factor and thus cheapen the cost of supply (§ 860). The electric flat-iron is almost a necessity in every household, as the Americans long ago found out; and on a farm, where there is constant home washing to be done, it is especially valuable. Nowadays, in the home counties at least, a large number of farm houses cater for the country rambler, and in this respect electric toasting, kettle boiling, grilling, etc., will prove useful.

Having gone so far, the farmer will naturally prefer to use electric light to relieve the gloom—and the traps in the way of muck-heaps—by an occasional light in the farmyard and barns, and to light his cow-house and stables properly. Not only will his fire risk be thereby relieved—with presumably a reduction in the premium—but cleanliness will be possible in a way that it is not with the hurricane lantern and smelling oil. By means of multiple switching (§§ 502, 503), Mr. Matthews points out * that both convenience and economy will be obtained, and ‘as the stockman walks round tending to his cattle he can always be working in a good light without wasting it elsewhere.’ With good lighting, one-third of the time usually occupied in feeding livestock can be saved; and, in a milking barn, the milk that is *not* accidentally spilled due to bad lighting conditions will more than pay for the cost of the electric light.

849. Industrial Motive Power on the Farm.—In subsequent paragraphs various uses of electric motors in agriculture are dealt

* *El. Rev.*, Vol. 93, p. 453.

with, while motors, motor control, and electric driving and hoisting are the subjects of Chapters 28 to 31. Here it is only necessary to point out that the keynote of any adaptation of motors to the special needs of the farm must be simplicity and fool-proofness; for the agricultural labourer is seldom mechanically minded, even if his master may have 'a little knowledge.' *

In addition, motors for use in the fields—even when housed in portable trucks—should be enclosed and weather proof; and for security it is desirable that those in farm buildings should be of the same construction, owing to the amount of fine dust inseparable from barns and thrashing floors. As to rating, the wisest course after electricity becomes available is to run each successive piece of machinery from a motor, with measuring instruments in circuits, so as to ascertain precisely what power it requires before proceeding further; thus avoiding both the Scylla of excess expenditure and the Charybdis of under-power. Much depends on the present condition of the machinery, and on how often it has been laid by for six months without having been cleaned up or oiled. Generally speaking, the 3-phase squirrel-cage type of motor will be the best for all-round use.

850. Barn Line-Shaft and Portable Motors.—There are difficulties in applying the individual drive (§ 748), which is the ideal of electrical engineers for most collections of machinery, to the heterogeneous assortment of machines found in farm buildings. A single motor, whether fixed or peripatetic, has a better chance of being looked after than half a dozen; and most of the apparatus requires comparatively little power, and this at varying times, so that one motor can serve a number of different machines.

On the other hand, Mr. Matthews writes: 'The experience of Continental farmers, who start out with a couple of portable motors, in five to seven years' time, is that the individual drive is preferable. Theoretically it is economically wrong, as the load factor is so low, but in practice, men's time and convenience have to be taken into account. Also machines can be placed in the most convenient position for their work.'

* Not long ago the present writer in the course of a walk came across a farmer and two labourers held up over a two-horse reaper that would not bind the sheaves. They were going off to the town in a Ford car to bring out a mechanic, none of them having the haziest notion of the gear. A washer out of the spares box put matters right in five minutes.

Generally a line-shaft exists where a steam engine at present does the work, and the corn and cake crushers, root and chaff cutters, etc., are driven by belting. Assuming that the shafting has been in use for many years without examination, it will probably need realignment and fresh bushings to the bearings, in which quite a large number of units (kWh) may otherwise be unnecessarily wasted annually; ball bearings are being used in many places on the Continent. Most farm buildings are old and somewhat decrepit, which does not make for good construction.

As an alternative to a line-shaft, especially where this is not already in being, a portable motor on a wheeled truck may be employed, fed by a flexible cable of the hardy type used in mining (§ 820); a method to be recommended to a farmer for a start. One such is illustrated in Fig. 394, facing p. 498. This particular motor truck is designed for hoisting produce, such as sacks of corn or bales of fodder, up to 3 cwt.; cable-type flexible being used for connecting it up.

On the Continent motors are specially designed and built for agricultural work, as the standard designs are often unsuitable on account of the exposure they have to withstand. Continental agricultural motors usually run at about 1 400 r.p.m. but speeds up to 3 000 r.p.m. are sometimes employed. Both there and in America* all the usual devices for speed reduction have been tried out; pulleys and belts, jockey pulleys of various types, back-gearred motors, friction-disc drives, etc.; among them (on gear-wheel speed reduction motors), a novelty in the form of a hollow tubular driving rod with a universal Hooke joint at the end, to save exact alignment.

The thrashing machine, if of the complete type usually fixed in the barn (as is preferred), will require its own motor, of much larger output (viz. 20 to 25 H.P.) than is needed for the smaller machines. Thrashing machines of the portable type, lacking many of the subsidiary devices, and suitable for use in the field, consume about $\frac{1}{3}$ of this power. Generally speaking, a 5 H.P. portable motor will do everything that is required on a farm except ploughing and thrashing, though a smaller one will generally be useful as well.

Where fixed thrashing machines are installed, the handy

* See *Power Plant Engineering*, Aug. 15, 1925, p. 854.

auxiliary motor can be used to convey the sheaves to the thrasher; take away the thrashed straw to the barn or yard; elevate the grain to the granary; and blow the chaff to the chaff-room; thus reducing the thrashing crew from a dozen to three or four. Owing to the steady drive, electric thrashing increases the saleable grain by about 5 %.

Among the various machines used in the farm buildings, chaff-cutters and corn-grinders are mentioned above; the former require from 2 H.P. and consume from 5 to 7 units (kWh) per ton cut, while the latter consume about 5 kWh per ton. Both these are very convenient for filling up hollows in the load curve, as they can be put on at odd times. Circular saws and brushwood cutters are often used, and some data relating to them are given in paragraph 858.

851. Electric Ploughing.—Any form of mechanical ploughing has the immense advantage of being able to turn up a far deeper furrow, of more uniform depth, than is possible with horses; just as the horse plough goes far deeper than the primitive ox-drawn wooden ploughshare of the East. Depth, and especially uniform depth, is always of advantage in good soil, though more so for some crops than others: *e.g.* it is the basis of successful sugar-beet growing. Furthermore, if sufficient power is provided, multiple ploughs can be used and a wide strip ploughed (up to 4 ft. or so) instead of a single furrow only. Mechanical ploughing has long been used, and in recent years electric ploughs have been employed by the hundred on the Continent—in France, Italy and Germany in particular—as well as experimentally in Canada and the U.S.A.; but Mr. Matthews' own appears to be the sole survivor here at present. And yet this work offers by far the heaviest load of all farm work, as stated above.

Mechanical systems of ploughing now in use are either of the automobile tractor type, with petrol engines for the most part, or of the steam or oil-driven rope-haulage type. The former has the disadvantage of imposing a heavy weight on the ground where the wheels run, and thus partly neutralising the effect of opening up the ground by forming a 'pan' below the furrows. The tractive resistance to the passage through the ground of a plough is both very great and very variable, according to the state of the ground—whether dry or wet; the nature of the soil; stones met with, etc. Experimental work at Rothamsted, confirmed by full-scale

tests on Mr. Matthews' farm, shows that the resistance can be reduced by as much as one-third by causing a current to pass between the coulter and the ploughshare, which causes a film of moisture to be formed between the furrow slice and the 'mould board' which turns it over. The accidental electrification of the driver's seat, however, of which an instance has been recorded, is inadvisable.

By Tractor.—Electric ploughing by means of a tractor involves the use of a trailing cable, which puts it at a decided disadvantage, though Mr. Matthews favours the method for the small farmer, partly because the tractor can be used for other purposes also. To suspend the trailing cable from a captive balloon, as has been done in Italy,* seems a trifle far-fetched as a solution of the dragging difficulty. A preferable method, though not altogether free from the dragging objection, is to pay out the cable from a drum on the tractor on the outward furrow and rewind it on the return trip; or to adopt the principle of the McDowell plough,† which, while incorporating this feature also, eliminates any dragging at all by using in addition a special cable trolley or portable pole for the main lead to the plough cable. A 30 H.P. tractor plough, according to Mr. Matthews, can deal with 6 acres per day to 8 in. depth, equivalent to 28 units (kWh) per acre.

By Rope Haulage.—Alternatively, electric ploughing is effected by means of wire-rope haulage, in one of the ways used for steam ploughing; a close parallel to the haulage of trucks in colliery workings (§ 831). In almost every case a double-ended multiple-share balance plough is used, so that it ploughs a wide strip of several furrows and need not be turned round at the end of its travel; it is clamped on to a wire rope which supplies the direct motive power. In this system the compressing effect of a heavy tractor on the soil is avoided. There is hardly a limit to the power which can be applied, where circumstances demand it. Some of the Continental single-drum winder (Howard or Fiskens) equipments have from 30 to 60 H.P., 3-phase, 500 V induction motors.

The systems of applying rope haulage to ploughing, mentioned

* *El. Rev.*, Vol. 101, p. 898.

† *Ibid.*, Vol. 99, p. 4, and Vol. 101, p. 1013.

§ 851 ELECTRICAL ENGINEERING PRACTICE

in the Report of the Electricity in Agriculture Committee to the Council of the I.E.E. * comprise:—

(c) By means of two stationary motors placed one at each side of the field to be ploughed, with a single steel cable traversing the distance between them, the plough being hauled in one direction by one motor and in the other direction by the other motor.

(d) By means of a single movable motor placed at one side of the field and a movable anchored pulley at the other, the plough being moved from one side to the other by a steel cable which passes from cable drums on the motor round the pulley.

(e) By the Howard or Fiske system, where a single fixed motor is used and, by means of ropes with movable anchored pulleys, the plough or other implement is drawn backwards and forwards across the field.

The Tescari system also has the advantage that the single motor truck is kept stationary. It has a double winding drum and the wire ropes run round the field instead of merely across it. Guide pulleys are used at the four corners of the field, of which two are mounted on trucks, and the plough runs between these two, which are moved along as the work proceeds.

Mr. Matthews states † that 'the wire-rope system, with motors of 60 to 150 H.P., has an enormous capacity for work, up to 30 acres a day, as against only an acre a day for horse ploughing'; but he considers the flexible-fed tractor of about 25 H.P. more suitable for the individual farmer. A communal plough—worked co-operatively—can be operated, he considers, ‡ on 200 days in the year—a great consideration, in view of the fact that it requires more power than any other farm operation; the estimate seems rather optimistic, but it has actually been worked to by several ploughing sets in France in the last three years. In a paper read before the I.E.E. § Mr. Matthews gives the following table of costs, based on 200 working days, with a life of 15 years for the apparatus and of 2 years for the cable, but exclusive of 'overhead charges.'

For deep ploughing the cost of current only may amount to 5s. per acre, bringing the total cost of electric ploughing up to from 8s. to 9s. 6d. per acre.

These figures may be compared with those given by the Electricity in Agriculture Committee of the I.E.E. || *viz.* :—

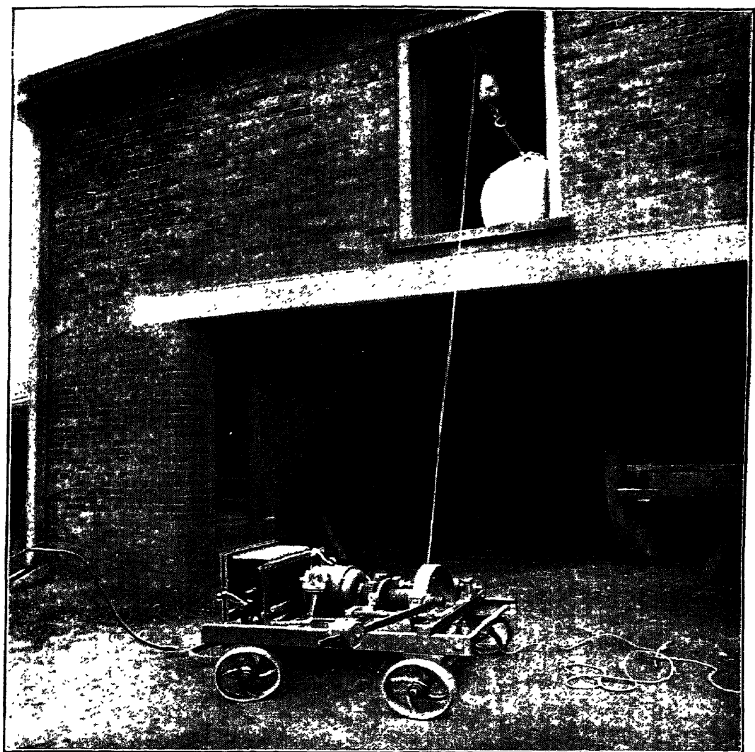
* *Jour. I.E.E.*, Vol. 63, p. 838.

† *El. Rev.*, Vol. 99, p. 133.

‡ *El. Rev.*, Vol. 101, p. 1013.

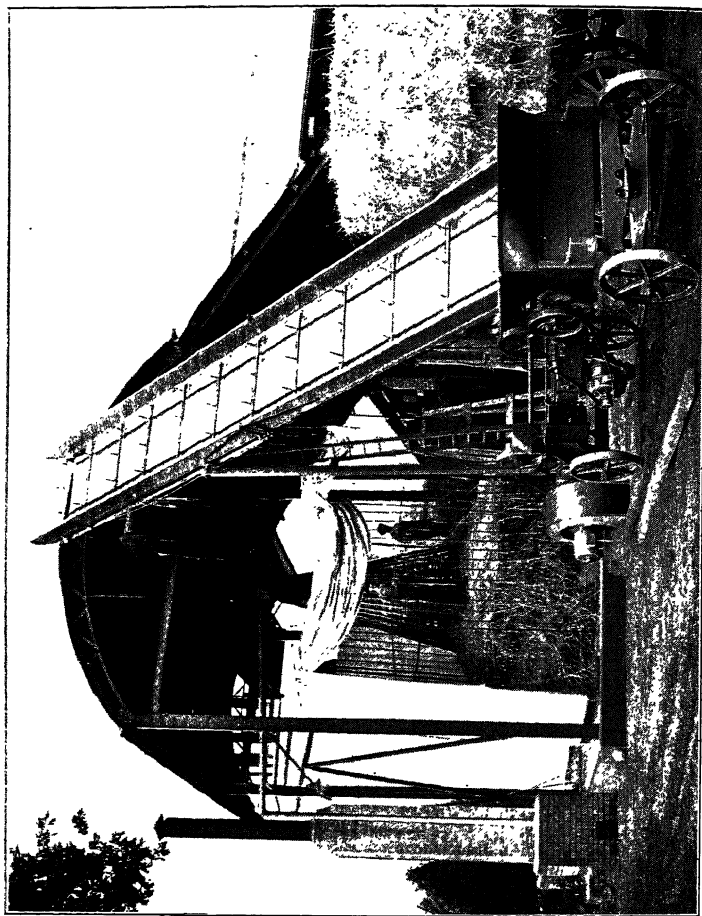
§ *Ibid.*, *loc. cit.*

|| *Jour. I.E.E.*, Vol. 63, p. 840.



Metropolitan-Vickers Electrical Co., Ltd.
FIG. 394.—Portable motor on wheeled truck with hoisting winch.

[To face page 498.]



Metropolitan-Vickers Electrical Co., Ltd.
owing heating arrangements.

ying

[See page 601

Steam ploughing . . .	15s. to 25s. per acre.
Tractor ploughing . . .	17s. 6d. to 30s. per acre.
Horse ploughing . . .	20s. to 35s. per acre.

Ploughing equipments can be so designed as to be capable of use also for harrowing, rolling and sowing.* When used for ploughing, the consumption varies from 15 units (kWh) per acre after rain up to 72 units (kWh) per acre in dry soil, and according to depth.

TABLE 180.—*Cost per Acre of Electric Ploughing, Ordinary Soil, from 6 to 8 in. deep.*

	Double-rope System with Two Haulages.	Modified Ditto with One Haulage and Anchor Wagon.	Anchor System with- out Pulley Wagons.	Tractor.
	s. d.	s. d.	s. d.	s. d.
Depreciation . . .	0 8½	0 8	0 6	0 6
Interest at 6 % . . .	0 8	0 7	0 5	0 5
Cable . . .	0 8	0 6	0 3	0 5
Repairs . . .	0 8	0 7	0 3	0 5
Labour . . .	1 8	1 5	3 0	1 4
Energy at 1d. per kWh .	1 3	1 6	1 8	2 0
Total per acre . . .	5 7½	5 3	6 1	5 1

852. Electrical Treatment of Green Fodder and Corn.—
Ensilage.—The use of the silo has not become general in this country, in which above all others the climate makes it desirable; in a cycle of wet and sunless summers, such as occurred from 1922 to 1927, the hay crop is mostly ruined when it could be saved either by artificial curing or drying, or by green storage. In its simplest form the silo needs no extraneous aids; a shallow pit is dug in the field and the freshly cut grass is stacked in and above it and then covered completely over with the excavated earth. The operation of stacking and covering is quickly done, and the fodder is so highly compressed that although it is fermented it cannot fire spontaneously as a wet hay rick will often do. The proof of the silo, as of the pudding, is in the eating; and beasts readily consume this primitive ensilage; but considerable skill

* R. E. Neale, *El. Rev.*, Vol. 87, p. 507.

is needed in making it, or sour silage is produced—which is the reason it has gone out of fashion. The modern silo is enclosed by walls, generally in the form of a cylinder, in order to gain height and adequate compression. If metal plates are made to cover the whole of the top and the bottom, according to the method developed by T. Schweizer in Germany, a current can be passed through the damp mass,* the lower plate being earthed. Where 3-phase supply is on tap, three separate silos are arranged on the phases, with the lower plate as the earth star point. This is not an electrolytic, but a heat process; so that either D.C. or A.C. can be used, at (say) 220 or 380 V. As soon as the current is turned on, the cells in the plants cease to function, and much valuable protein is thus saved from destruction. The charge is continued for three or four days, the current rising gradually from 3 A or 4 A to about 50 A for a silo of 3 500 cu. ft., and the temperature rising to about 50° C., so that most of the destructive bacteria are killed.

The consumption is about 23 units (kWh) per ton of fresh-cut material and 50 units (kWh) per ton of cured silage; which also gives the latter figure per head of stock to be fed. It is not advisable to fill the silo before beginning treatment or the electrical resistance will be too great at the voltages usually available. Mr. Matthews (*loc. cit.*) points out that the best results are obtained by working on each layer of about 5 to 6 ft. thickness as it accrues.

Electrical Drying of Crops.—Artificial drying is applicable both to grass (for hay, as distinct from ensilage) and to cereal crops. So long as the weather is good, sun drying in the field is likely to hold its own, both in cost and often in quality; but some proportion of the 640 000 000 units (kWh) which, it has been suggested, might be employed in electrical drying will no doubt serve to counteract the vagaries of our climate. The method employed is to stack the crop as it is cut, over an air-distributing framework in the form of a hollow central cone, supplied with air by a duct fed by a pressure fan (§ 763). Either air at the ordinary temperature or hot air may be employed. Ricks up to 8 tons of finished weight can be treated by the hot-air process (developed at

* *Electrical World* (New York), quoted in *Beama Jour.* Also *El. Rev.*, Vol. 92, p. 566.

the Institute of Agricultural Engineering in Oxford from the earlier work of Matthews and Tinker) in 8 to 12 hours. It is to be feared that oil or other fuel will generally be used in preference to electricity for heating the air, if this system comes into full use; but the fan offers a useful load.

Fig. 395, facing p. 499, illustrates a crop-drying outfit designed by Colonel Lyon for use on his farm, on the principle of the afore-mentioned patents, with air heating arrangements consisting of hot-water pipes round the central conical air tower and a small furnace. The apex of the cone is covered, and air is driven through the duct into it from an electric fan, whence it passes between the hot pipes and through the stack.

Mr. Matthews favours the atmospheric air method of curing, after considerable experimental work, owing to its lower cost and the very much larger quantities that can be dealt with at one time. Under conditions of wet weather, the hot-air system is, however, necessary in conjunction with the other. With a rick consisting of 50 loads of grass and ending in 25 tons of artificially cured hay, the total energy used was 34 kWh or 1·3 kWh per ton of product.* The quality is stated to have been better on an average, and the cost less, than with sun curing and constant manual turning over during the process; power cost 2s. 3d. per ton, and the capital cost of the fan was £50. Corn can be similarly treated and then thrashed at once.

In America the continuous method of drying green crops—corn and fodder—is in use.† The crop as harvested is brought to an elevator with a 10 H.P. motor, and is then passed down through a series of rollers which comb it out into a uniform mattress 8 ft. wide and 10 ins. thick. This travels on a conveyor band, driven at 5 ft. a minute by a 10 H.P. motor, through a drying tunnel, served with air at a temperature between 250° and 400° F. (according to the crop) by a 30 H.P. motor fan with a capacity of 80 000 cu. ft. of air delivered per minute. For heating the air, anthracite is *directly* used owing to its smokelessness, the consumption being 1 lb. per 2 lb. of dried crop. The plant referred to, which is the second designed by Mr. Mason, is installed on a 600-acre arable farm in Plainsboro', New Jersey. It cures and bales 20 tons of

* *El. Rev.*, Vol. 91, p. 287.

† Mr. Matthews, *El. Rev.*, Vol. 100, p. 549.

hay in 10 hours, with $8\frac{1}{2}$ tons of fuel for heating. It cost £4 500 to equip, and costs about £4 200 per annum (including all labour), the resulting crop being worth £12 000. An interesting feature is that it is possible to keep it in operation for six months in the year, thus bringing about factory conditions of regular work for the men.

853. Irrigation, Pumping, and Draining in Agriculture.—

Where there is sufficient natural slope in the ground, land drainage is to a large extent automatic, or at most requires the provision of furrow draining by means of pipes or deep-cut rubble-bottomed 'clinker drains'; but on flat or waterlogged land pumping is often necessary. In some cases this is combined with water supply, either for domestic use or for irrigation. Much of this is done by wind power, but there is also great scope for electricity. The prehistoric method of the 'Karese,' used to this day in Northern Asia, taps underground water by means of a series of wells connected by tunnels, starting on the higher ground and descending towards the valleys, where it reaches the surface. A modern parallel or substitute is the wire-wound percolation 'tube well,' served by an electrically-driven centrifugal pump (*see below*).

Pumping for water supply.—Apart from special applications for drainage and for irrigation, pumping is required on most farms for water supply for man and beast. For general information on the subject of electric pumping §§ 767 *et seq.* may be consulted; and for the cost of small pumps, see § 573 (Vol. 2). The modern windmill naturally obtains most of this load, but as wind power is both precarious and uncertain in amount and duration, some more secure reserve is generally added. Once electricity is installed, this reserve will naturally take that form in preference to the usual oil engine.

Pumping for Irrigation and De-watering.—What the windmill has done in the past, and is still doing, to reduce flooded or waterlogged land to a cultivable state is to-day often done by electrical pumping and will to-morrow be done to a far greater extent; for a pumping load in almost every case is one that can be temporarily shut off at times of peak load and thus used to fill in the hollows of the load curve. This property is equally useful when the pumping is purely for irrigation or when it is combining the double function of de-watering and irrigation, provided of course that the supply of power is from a public plant or a plant

having other load, and not from a private plant erected for this work alone as in the Indian examples that follow.

The climate of Great Britain for the most part renders irrigation (other than by hose-pipe) unnecessary; but in arid countries it is often the life-blood of a large population on land that without it would be desert. With irrigation purely by gravitation canals we are not here concerned; but wherever these are used there are likely to be extensive areas just 'out of command' of irrigation, *i.e.* at a level (whether six inches or a hundred feet) above that of the canal.

Furthermore, these canals almost invariably have falls on them at intervals, to ensure correct grading.* Here then are the ideal conditions for developing power at a fall (§ 218) and using it to pump water from the canal on to distributary channels at the higher level. From an economic point of view it follows that, the lower the super-elevation of the uncommanded land the greater the area (in inverse proportion) that can be so irrigated from the power available at any fall. But so great is the yield of crops from some of these irrigated desert lands that it may pay to convert a six-foot canal fall into a sixty-foot lift of about one-twelfth of the water flowing through the wheels.

An admirable example of this is the installation, with which one of the authors was professionally connected, put in at Renala (Punjab) by the late Sir Ganga Ram. That far-seeing engineer, after a preliminary and successful experiment with steam plant in 1916, obtained from the Punjab Government a lease of nearly 80 000 acres (125 sq. mile) of sandy waste above the Lower Bari Doab Canal, on which he constructed a power station of 1 100 kW, using a fall of 6 ft. The scheme comprised 72 miles of new branch canals and distributaries, 626 miles of water-courses from which the water actually flows on to the land, 45 bridges and over 600 miles of roads together with seven pumping stations and transmission lines to them. The pumping heads vary from 4 to 8 ft. (static) and the 16 pumps have capacities from 6 up to 50 cusecs. Vertical shaft centrifugal pumps are used, driven by

* For the benefit of those who only know the navigation canals of the British Isles it should be explained that these are practically dead level in each stretch, and are only fed with just sufficient water to make up for what is lost or let down through the locks; but an irrigation canal is a flowing river, feeding thousands of tributary ditches, and must be so graded as neither to scour its banks nor unduly to deposit the valuable silt it carries along.

3-phase vertical slip-ring motors through epicyclic straight-toothed gearing. Apart from its technical interest, this work provides good agricultural land for a population of 100 000 settlers, mostly ex-service Indians. In California large areas are similarly irrigated from wells, the pump-houses being served from the hydro-electric plants which abound there.

Where an unlined irrigation canal of large capacity runs through porous soil there is very great soakage through the banks, and the sub-soil water is raised until its slope away from the canal reaches equilibrium; and similar effects occur at all the distributary channels and water-courses of the system. In some cases this results in complete water-logging of the land, with evil results in increase of malaria. An interesting experimental plant was put up a few years ago near Amritsar (Punjab) to deal with these conditions. Tube wells were sunk over the area, served by vertical centrifugal electric pumps, the power being obtained from a low canal fall. The point here is that the intensive irrigation of the land was carried on by means of water pumped from the saturated sub-soil into the water courses, so that the level of the water-table was gradually lowered; and, meantime, the water from the canal which had previously been poured on to the land with disastrous results was conserved in the main canal and used in the reaches lower down.

Pumping for Reclamation.—Parallel to the last-mentioned application is that of the reclamation of swamp or fen lands, actually flooded instead of merely water-logged, of which Holland affords the best-known examples. A case lately occupying attention in this country is that of the Ouse drainage in the Fen district. A suggestion has been made* for combining electrical pumping in this area with the provision of power for other agricultural purposes. Naturally gravitation would be used *pari passu* with pumping, where tidal conditions and ground slope admit. In many tidal 'saltings'—such as those in Essex—it would be a comparatively simple matter to build a mud embankment sufficiently inland to escape destruction, with both automatic tidal outlets and powerful centrifugal pumps. The pumping 'head' would be extremely low, and the 'duty' great, in proportion to the power required (§ 768).

* *The Times*, April 25, 1924, p. 6.

854. Haulage in Agriculture.—For general data as to haulage on rails, § 831 (Mining) may be consulted; and haulage on roads—or off them—only differs in the higher and less easily ascertained tractive resistance, which must be fabulous on the average farm road. For electric road vehicles, *see* Chapter 36; but battery cars are not likely to have much scope in the present connection, as the dead-weight of the batteries is serious, and even the hardest cell could not stand up to the ruts and pot-holes which constitute a track. Lifting and hoisting are dealt with in Chapter 31. There is scope for elevators of one form or another on most farms, where the laborious methods of our ancestors are still used, as instanced above in the course of the treatment of green crops (§ 852).

For tractors generally there are a variety of uses, but electricity is at a disadvantage compared with petrol. Either a trailing cable or a trolley line is needed. The trailing cable is liable to damage and heavy wear from being dragged, even if the heaviest type is used—and this will be both costly to provide and difficult to handle. Fixed trolley lines cannot economically be run except over definite tracks on the farm, leaving the questions of by-ways and of breaking bulk by transfer unsettled. Various ingenious schemes have been devised for the temporary erection of portable trolley lines, including one with a motor-driven friction clutch to keep the wire taut; but the system is on the whole not very practicable. It is best to realise and admit that there are limitations even to the uses of electricity.*

An A.C. supply has been assumed throughout this chapter as necessary for transmission and transformation for rural supplies, and as the accepted national system of the Central Electricity Board; but even the 3-phase induction motor is not altogether suitable for tractor work, while single-phase would be quite unsuitable. The power installed on electric tractors usually varies between 15 and 30 H.P., and in Sweden many such are in use, according to Dr. A. Ekstrom.† The 'caterpillar' type of tractor has obvious advantages, in its capacity for traversing any sort of ground, and so in a lesser degree has the modern 6-wheeled

* Reference may be made to a paper on 'Transport on the Farm,' read by Mr. Matthews before Section G of the British Association at Leeds, 1927.

† *El. Rev.*, Vol. 101, p. 558.

chassis. It is stated* that work can be found for a tractor on the farm for about 1 000 hours per annum.

855. Dairy Work.—In these days, when old plough lands are again reverting to pasture, the dairy is not only one of the most important features of the farm, but also the one in which the advantages of electrical working are most certainly realised. The milking machine will be driven better than by any other power; the operations of preliminary chilling, sterilising, separating, butter and cheese making, may all be performed, with perfect cleanliness and the minimum of manual labour, by electricity.

In the dairy of Messrs. Stapleton at Stoke Newington,† dealing with 2 000 out of a total of 6 000 gallons a day, electricity is used for cold storage; pasteurising; bottle-washing, filling, sealing, and labelling; cream preparation; water and milk pumping; and milk conveying. The bill for current amounts to about £500 per annum for 101 200 units (1926), at 1·25d. per unit (kWh), or 0·3 % of the selling price of the milk, etc. The maintenance costs are about £25 per annum, including inspection, lubrication, and insurance. Twenty-six motors are employed, ranging from $\frac{1}{2}$ to 12 H.P., and totalling 132 H.P., and the offices are equipped with radiators, fans, and cooling appliances.

Milking machines have now arrived at the stage of development where they can complete the operation with smoothness and speed as well as cleanliness. The consumption of energy (see § 858) varies with different machines from 1 kWh per milking time upwards, for 20 to 50 cows.

Pasteurising.—With the prohibition of boric and other preservatives, pasteurising has become additionally important. A plant for treating 2 000 litres (528 gallons) per hr. requires 100 kW input. The ordinary bacteriological tests applied to milk take about three weeks; and Mr. Matthews states‡ that an alternative method is to employ an incubator (§ 856) which can be maintained at 60° F. by means of a water jacket for the main cooling and an electric heater for the final control. A sample of milk which remains fresh for 24 hrs. at this temperature will be well within the limits of the permissible bacteriological content, viz. 30 000 per cu. cm.

856. Poultry Farming and Bee Keeping: Mosquitoes.—On the poultry farm electricity can play its part with profit in

* *La Revue Industrielle*, Sept., 1924.

† *Ibid.*, Vol. 95, p. 886.

‡ *El. Rev.*, Vol. 99, p. 131.

various ways, from the encouragement to lay more freely, *via* the incubator, to the treatment of the newly hatched chicks.

Light Treatment.—It is definitely established that hens will lay under the influence of artificial light in the off season to an extent that more than pays for the additional cost. Mr. Matthews recommends 0·8 to 1 ft.-candle illumination on the feeding floor for a period, varying with the season, before sunrise and after sunset; * and on his farm the light is brought up and extinguished gradually, so as to simulate sunrise and sunset, which appears to deceive the birds and cause them to prolong their feeding. This is nowadays arranged for by a suitable time-switch (§ 272, 374, Vol. 1). The short English winter day does not give enough time for the absorption of sufficient food.

The maximum demand is stated † to be about 1 kW per 1 000 birds. In one instance ‡ two batches of 450 fowls were compared, one with artificial lighting and the other as a 'control' without it. The result was a yield of 206 against 176 eggs during the winter days, and a net extra income of £33 at market rates.

Chick-Rearing.—Young birds are found to thrive better, especially in the winter, if exposed daily for ten minutes or so to ultra-violet rays from a mercury arc (§ 588) or an ordinary carbon arc lamp (§ 591); and the installation of these 'artificial sunlight' methods in the London Zoological Gardens has proved that they are beneficial to many creatures besides human beings—though, strangely enough, not to small tropical birds. It is also thought that ozone and the effects of a discharge from overhead lines (as in electroculture, § 857) are beneficial.

Incubation.—Between the egg and the chick comes the incubator, as the most important item from the electrical point of view. In an article on 'Some Radical Developments in Incubation' § in his series on Electro-farming, Mr. Matthews refers to his own work and to the results obtained by Mr. Llewellyn Atkinson, as described by the latter before the Society of Arts.||

* He points out that the domestic fowl originated in the tropics, where the variation in the hours of daylight is far less than here; but it may be urged, *per contra*, that birds in the wild state only lay in the one breeding season.

† *El. Rev.*, Vol. 91, p. 819.

‡ *World Power*, Oct., 1926, p. 185.

§ *El. Rev.*, Vol. 95, p. 884.

|| 'The Scientific Principles of Artificial Incubation,' by Lil. B. Atkinson, Past President, I.E.E. (*Jour. R.S.A.*, Nov., 1924).

Briefly, by means of thermostats it is possible to regulate the temperature in an incubator to a nicety, whatever method of heating is employed; and by means of an electric fan it is possible to keep the conditions uniform in a large incubator; but correction of the humidity, and of the quantity of CO_2 present, are also important. Mr. Atkinson has developed simple chemical indicators for both these factors, as described in the paper referred to. Furthermore, while it has long been known that the eggs should be turned from time to time, Mr. Atkinson discovered that there should be a considerable difference between the temperatures of the tops and bottoms of the eggs, as in Nature's way, and this has been effected by covering the eggs with a rubber sheet. Mr. Matthews sees possibilities—amounting perhaps to a prospect—of 25 million units per annum being used in this branch of farming. Percentage hatchings have been greatly increased by these improvements—from 55 to 95 %. Mr. Matthews points out that his own incubator (which, unlike Mr. Atkinson's, uses a fan) assists in keeping the temperature, humidity and CO_2 uniform, but fails to give the differential temperature between the top and bottom of the egg; on the other hand, it enables tiers of egg-trays to be used, and in practice the eggs are put in fresh in the top layers and moved downwards towards the bottom as incubation proceeds, hatching out on the lowest tray.

An electrically heated incubator of the ordinary type takes 11 units (kWh) to hatch out 60 eggs; * a 250-egg machine takes 16 units (kWh). With Mr. Atkinson's closed type, without a fan, the consumption would be less—perhaps by one-third. The huge electrically heated incubators used in the U.S.A., and producing 120 000 chicks a week, consume from 50 000 to 80 000 units (kWh) a week with a maximum demand of 400 kW and an excellent load factor.†

Bee Keeping.—It may be added that by keeping all the beehives together in a shed, and by lighting and warming it, Mr. Matthews has obtained a considerably increased yield of honey, due to a strong hive of bees being ready for the apple blossom season, in spite of the earlier inclement weather that occurs in four years out of five in this climate.

Mosquitoes.—An unusual use of electricity has recently been

* Mr. Matthews, *loc. cit.*

† *El. Rev.*, Vol. 91, p. 819.

described* for the destruction of mosquitoes. A lamp emitting ultra-violet rays is used to attract them and a fan-driven vacuum apparatus to impound them. It has long been known that certain colours attract mosquitoes in preference to others, but full use has not been made of that fact.

857. Electro-Culture.—The fact that the Ministry of Agriculture appointed an Electroculture Committee in 1922, under the Chairmanship of Sir John Snell (Chairman of the Electricity Commission), shows that this branch of agriculture has great promise; and the research work carried out at the Rothamsted Experimental Station, at the Harper Adams College, at Lincluden, at East Grinstead, and by private workers has borne out the promise in many respects and on most counts.

Seed Treatment.—Hitherto the hopes at one time entertained, as to the improvement of seeds by electrical treatment, appear to have been dashed by the systematic experimental work carried out at Rothamsted and by Messrs. Sutton at Reading.† The Wolfryn process consists in immersing the seeds in a solution of salt and water, or calcium chloride and water, through which a current is passed, with subsequent drying at 100° F. An application of electro-magnetic separation, of proved value as regards clover seed, is referred to in § 997 and may be capable of extension.

Hail Prevention.—In § 996 experimental work in the matter of smoke reduction and mist dispersal is briefly referred to; and analogous methods of electrical precipitation may serve to ward off hailstorms in the future.‡ In these matters Sir Oliver Lodge has done pioneer work which will bear fruit in due course.

Heat Treatment.—In place of the ordinary under-bed of manure in a frame, high resistance wires have been run zig-zag under the soil, and 500 W or so (according to the size of the frame) passed through. Amongst the unrehearsed effects, this hatches out the slugs; but it is also effective. The same method is applicable to greenhouses. §

Light Treatment.—More certain, however, are the results achieved directly on the land and on crops, whether in glass houses

* *El. Rev.*, Vol. 112, p. 361.

† Bulletin 11, 'The Electrification of Seeds by the Wolfryn Process'; Sutton & Sons.

‡ *Vide* account of the Marcillac Hail Net in the *El. Rev.*, Vol. 81, p. 94.

§ Electric Heat in the Garden, R. B. Matthews, *El. Rev.*, Vol. 103, p. 229.

or in fields. The action of artificial light from ordinary metal filament lamps is very beneficial (cf. § 856) and the effect of 'artificial sunlight' from mercury vapour or arc lamps is equally pronounced on the human or other animal bodies * and on plant life. Just as ordinary sunlight brings on blossoms and ripens fruit, so, in an even more marked degree, is it with the concentrated rays of artificial sunlight. As the demand for things that are out of season continually increases, so science provides for it by these means and by cold storage. Mr. Matthews has used 1 000 W Mazda lamps, with 2 ft. reflectors, for pot-culture under glass:—†

'Daffodils and Lent Lilies, when placed under the light for six hours a night, flowered in four days, growing about $\frac{3}{4}$ in. a day. Narcissi flowered in seven days. . . . The "control" plants, placed away from the light, took four weeks to flower.'

Even a single night's treatment was found to have a startling effect. Seedlings, exposed to intensive illumination for one night, after transplantation, did not wilt as they always do otherwise. Possibly similar treatment before transplantation would be effective, and, if so, it would put the matter beyond the present stage of pot-culture. Mr. Matthews points out that by using the light between midnight and 6 a.m. it would be a useful load at the slackest time, for which special rates might be obtained. He further records‡ that beans were grown under 500 W gas-filled lamps, placed 3 ft. above the ground, and giving an intensity of illumination of 700 lumens (§ 580, Vol. 2) per sq. ft. of ground. The power consumption over the bed in forty-four days, during which the lamps were kept burning day and night, was 55 W per sq. ft. The rate of growth and development was nearly double that of a control plot under daylight only.

High-tension Treatment.—In addition, the influence of a high-tension brush discharge over any area, covered with a suitable net-work of overhead distributing wires, is generally very marked as compared with neighbouring control plots not so treated. The discharge may be obtained by spark coil methods or, on a larger scale, by transformer and rectifier, the overhead network being charged at 80 000 to 100 000 V. The Ministry of Agriculture Committee on Electroculture, referred to above, had much experi-

* It may be as well here to repeat the warning so often given, as to the danger of ultra-violet rays to eyesight. Goggles are invariably needed.

† *El. Rev.*, Vol. 97, p. 685.

‡ *Loc. cit.*

mental work done in the way of pot-culture on these lines, as well as some field work, mainly to determine at what stage of growth the treatment is most advantageous.* Marked increases in *grain* yield were obtained, up to 118%, though the increase of *total* yield was small—showing an acceleration of reproductive growth apart from, and apparently at the expense of, mere vegetable growth. The second month of the growing season was the one in which treatment had the best results. From the Fifth Interim Report of the Committee, of which a full abstract appeared in the technical press, the following is taken:—

A field installation was erected on Fosters Field at Rothamsted in 1922 on an economic scale (*i.e.* with poles spaced widely, and with high wires, so that no undue interference was caused to farming operations), the object being to determine the kind of installation suitable for the purpose, the current required, and the cost. The area under the influence of this installation (assuming the discharge to be effective for 15 ft. beyond the wires on all four sides) is about 5 acres. The installation consists of nine creosoted poles each 24 ft. in length of which 6 ft. is sunk in the ground; four of the poles are in the field and five in the hedges. The supporting wires at the ends of the area and in the middle of the area are of rustless mild steel (No. 12), each 125-150 yds. long. There are twelve thinner wires (No. 26) of silicium bronze, each 200 yds. long. The porcelain rod insulators are 18 ins. long. The cost of the installation and its erection (materials, carriage, labour, travelling expenses), and supervision was £52, or about £10 per acre. The Agricultural Electric Discharge Company has supplied the Committee with estimates of the cost of erection of an economic installation in areas of various sizes. The cost of the poles, insulators, and wires for 100 acres is £215, *i.e.* slightly over £2 per acre, so that it is obvious that the price for small installations is no criterion of the cost in actual practice. The fact that fields are not of the size of 100 acres hardly affects the question since several fields can be included in one installation. The measurements were taken at Rothamsted (1) on the wheat plot; (2) on the stubble after the wheat crop was removed, and (3) on the field under the economic installation. Before these experiments doubt might well be entertained whether even a rough estimate of the current passing to the crop could be derived from the measurements of the current passed into the overhead wires. It now seems fairly certain, however, that with overhead wires whose distance apart is not much in excess of their height, fully half the current supplied to the wires may be expected to reach the crop. It is also clear that a very considerable area surrounding the electro-culture area, especially on its leeward side, receives a discharge much in excess of that which passes normally between air and earth.

The results obtained in 1922 indicated the importance of concentrating attention on pot-culture experiments, small plot experiments and laboratory work. The experiments of 1922 on the effect of the discharge during different growing periods and different daily periods are being repeated in 1923; the effect of very weak currents and the effect of screening the plants from the normal atmospheric current are again being studied.

It is clear, says the Committee, that the electro-culture problem is an intricate

* *El. Times*, Aug. 2, 1923, p. 120.

one with both physiological and agricultural aspects, and one which is far from being fully elucidated. The Committee's investigations, however, may be fraught with the most important consequences to agriculture, as the results hitherto attained clearly indicate.

Further information concerning investigations in this field is to be found from time to time in the official Journal of the Ministry of Agriculture.

For obtaining the necessary high-tension discharge, several methods are available.*

Static machines give the best results within their capacity, but this is too small for commercial areas. They are defective in often failing to excite and in reversing their polarity, and must be kept absolutely free from damp air.

Ordinary *high-frequency apparatus* is not satisfactory, owing to difficulties in charging the network evenly if there is appreciably self-induction.

A *step-up transformer* is the cheapest and most convenient source of high potential; but the A.C. requires rectification (§§ 415 *et seq.*, Vol. 2). The kenotron (§ 419) or other valve device is, however, considered preferable to a rotary rectifier.

For small plots of land, not large enough to warrant such an installation, an *induction coil and interrupter* is recommended, with slow 'make' and extremely rapid 'break,' so that while the peak voltage may be 90 000 V at break it is only a few thousand volts at make.

858. Power and Energy Data.—In so comparatively new an application of electricity as is here considered, it follows that data as to the consumption of power and energy vary greatly in different localities and under different conditions. Table 181 is calculated from a chart based on the statistics of the United States Department of Agriculture,† showing the derivation and distribution of total energy consumption (15 788 million H.P.-hrs. per annum) between various power sources and applications. The relative distribution doubtless varies widely in different localities, but these figures afford a useful guide for general estimates:—

* *El. Rev.*, Vol. 81, p. 22.

+ *Ibid.*, Vol. 96, p. 997.

TABLE 181.—*Percentage of Total Agricultural Energy Consumption from Various Sources and in Various Applications.*

		Approximate Percentage of Total H.P. Hrs. Consumed.		Approximate Percentage H.P. Hrs. from Various Sources.	
Haulage work on the land	Ploughing and listing	15.8			
	Fitting ground . .	6.3			
	Planting and seeding	2.5			
	Cultivating . . .	6.3			
	Harvesting . . .	5.1			
	Haying . . .	5.7			
	Miscellaneous . .	6.4	48.1		
Haulage .	Farm haulage . .	7.6			
	Road haulage . .	14.9	22.5		
Stationary .	Thrashing . . .	7.6			
	Pumping . . .	10.2			
	Miscellaneous . .	11.6	29.4		
Total		100.0	100.0		100.0
				Animals . . .	61.3
				Stationary engines	12.3
				Petrol tractors .	9.7
				Steam tractors .	6.4
				Electricity . . .	5.4
				Trucks . . .	3.6
				Windmills . . .	1.3

From the Report of the Electricity in Agriculture Committee to the Council of the I.E.E.* the following figures of consumption (Tables 182 and 183) are taken :—

TABLE 182.—*Consumption of Energy (in Buildings) on a Farm of 150 Acres.*

	Units (kWh per Annum).	Units (kWh per Acre per Annum.)
Lighting house	100	0.67
„ buildings	150	1.0
Motive power, barn and dairy	1 500	10.0
Heating and cooking	1 500	10.0
Total	3 250	21.7

* Jour. I.E.E., Vol. 63, p. 839.

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TABLE 183.—*Average Data of Thirty-three Farms (230 Average).*

Number of motors per farm	1.4
Average H.P.	10.0
Electric lamps per farm house	18
„ „ in buildings	18

	Units per Annum.	Units per Annum per Acre.
Consumption, annual, lighting	370	1.6
„ „ heating	470	2.05
„ „ power	1 370	5.95
Average Total	2 210	9.5

On the Continent, the Report states, long-established electrically run farms use an average up to 22 kWh per acre per annum. From America * the figures in Table 184 originate, through an analysis by the Home Economics Division of the Iowa State College:—

TABLE 184.—*Average Energy Consumption on Iowa Farm.*

Device.	kWh per Month.	
	Per Family.	Per Person.
Electric range	102	25
Refrigerator	28.45	11.15
Ironing machine	2.8	0.46
Iron (used with it)	3	0.5
Electric cooker	5.5	0.9
Waffle iron	2	0.5
Washing machine	2	0.5
Percolator	6	1.5
Toaster	1.2	0.3
Glow heater	5	0.7
Water pumping (shallow)	795 gals. per kWh	
„ „ (deep)	576 „ „	
Incubators	370 Wh per chicken (79 % hatched)	
Water heater (60-70° inlet, 128° outlet)	4.5 gals. per kWh	

According to C. D. Kinsman of the U.S. Department of Agriculture,† the average energy consumption per acre for crop produc-

* *El. Rev.*, Vol. 99, p. 907.

† See also *El. Rev.*, Vol. 96, p. 997.

tion (*i.e.* per season and including all forms of power) in the United States is as in Table 185:—

TABLE 185.—*Energy Consumption per Acre for Crop Production.*

	kWh per Acre.
Corn, grain	14 to 26
„ silage	24 „ 37½
Small grain	10½ „ 18½
Hay . .	8 „ 9
Potatoes .	20 „ 43
Tobacco .	20 „ 37½
Cotton .	15 „ 22½
Rice . .	28½ „ 30
Sugar beet	30 „ 52
Fruit .	33½ „ 52

From various sources, but mainly from a paper by C. D. Kinsman * of the U.S. Department of Agriculture, the figures in Table 186 are compiled:—

TABLE 186.—*Energy Consumption for various Farm Operations.*

	Units (kWh).
Hauling over ploughed ground, per ton-mile	0·67 to 1·08
Thrashing, per 100 bushels (small machines, 5-7½ H.P. ; large, 20-30 H.P.)	7·5 „ 30
Elevating grain, per 100 bushels	0·15 „ 0·37
Pumping water, per 1000 gal.-ft.	0·009 „ 0·018
Ploughing clay loam, per acre (Mr. Matthews gives up to 23 units (kWh) for deep ploughing)	6·7 „ 9·7
Rolling land, per acre	0·3 „ 1·5
Drilling grain,	0·3 „ 1·34
Mowing,	0·56 „ 1·12
Raking,	0·22 „ 0·6
Corn planting	0·75 „ 1·86
„ cultivation ,	0·75 „ 1·86
Potato digging	3·7 „ 5·6
Chaff cutting, per ton cut per hour	3½ „ 5½

(N.B.—Converted to British measures.)

From Denmark † it is stated that the smaller portable thrashing machines require from 5 to 7½ H.P., while large fixed machines take from 20 to 30 H.P., but the quantities dealt with are not stated. Chaff cutters need a 2 H.P. motor. Corn milling machines,

* *El. Rev.*, Vol. 96, p. 997.

† V. Faaborg Andersen, *loc. cit. ante*.

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for grinding corn for fodder, afford a useful load for filling up hollows in the load curve, as the work can be done at any time when the portable motor is free. The energy consumption in Denmark, according to the above authority, is as in Table 187.

TABLE 187.—*Energy Consumption on Farms in Denmark.*

Farms without milling machines	4.4 units (kWh) per acre.
Farms with milling machines	14.4 " " "
Average, whole district	6.8 " " "
Maximum	21.2 " " "

The following additional data will serve for comparison:—

A farm circular saw uses from 0.03 to 0.04 units (kWh) per cu. ft. of wood sawn.

Chopping brushwood requires from 3 to 5 H.P. and consumes from 1 to 1½ units (kWh) per load.

Hay baling requires from 2 to 3 H.P. and consumes about 1 unit (kWh) per load.

For oat crushing, the energy used is about 250 Wh per cwt.

Milking machines, for 20 cows in 1 to 1½ hrs., require 1 H.P. and consume 1 unit (kWh) per milk or 2 units (kWh) per day.

Mr. Matthews * gives the following data:—

Grass drying in stacks requires a 5 H.P. fan for 30 minutes a day, for 10 days.

Consumption in farm buildings alone (excluding lighting) varies from about 10 units (kWh) per acre of farm up to 100 units in specially fertile farms.

Consumption in farm house: lighting, 200 units (kWh); heat and power, 800 units (kWh) per annum.

Ploughing, 33 units (kWh) per acre of arable land.†

Cultivation, silage and harvesting, from 25 to 45 units (kWh) per acre.

Average of 34 districts on the Continent, 52¼ units (kWh) per acre.

859. Ways and Means.—It has been indicated in the introductory paragraph to this chapter that finance is the chief stumbling

* *World Power*, Oct., 1926, p. 185.

† Mr. R. E. Neale (*El. Rev.*, Vol. 87, p. 507) gives from 72 kWh per acre in dry soil down to 30 kWh after rain.

block to progress in rural electrification; the successful farmer—for he must exist, though one seldom hears of him—is content to carry on by the methods of his yeomen ancestors, and the unsuccessful farmer cannot afford to do otherwise than carry on and await the millennium. The State, however, through its representatives, has been sufficiently impressed by the new vista opened up to have decided on the provision of power lines over the whole of Great Britain, eventually, which carries us forward through one very important stage.

Having gone so far, it is essential that a demand shall be created for this readily available power. If the individual farmer cannot or will not incur the necessary expenditure, even though the annual charges due to it can be proved to give him a substantial return and a saving, the only alternatives appear to be co-operation between neighbours and State or local authority assistance. So huge is the expenditure to which the State is already committed over the 'grid' that it seems questionable whether any Chancellor of the Exchequer will go further; for there is a limit even to directly remunerative expenditure under the economic and associated difficulties of recent times; and rural electrification is admittedly somewhat speculative, as the weather is an incalculable element. The expenditure of local authorities is already often carried near to the danger point; but if any form of public assistance in finding capital is required, it would seem to be a matter for the County Councils—no doubt after the passing of enabling legislation. This assistance might take the form of comparatively short-term loans—maturing in five or ten years—for the provision of the overhead lines from each point of supply over the estate; in this way much overlapping could be avoided, provided the tariff difficulty could be overcome, as a boundary could be used on both the adjoining sides. The same principle might be extended to the purchase of such costly equipment as could be used successively by a number of farmers—especially ploughing outfits.

Co-operation between neighbours is certainly preferable to any form of public assistance, and has been practised abroad for many years, especially in marketing; thus in Denmark * the Agricultural Co-operative Societies began work with dairy and slaughter-house

* V. Faaborg Andersen, Secretary of the Danish Royal Electricity Commission; *El. Rev.*, Vol. 101, p. 292.

produce, and then went on to electric supply—first at low pressure and then on modern high-pressure lines. But in this country (*pace* the Farmers' Union) co-operation does not seem to flourish. Carried on by means of limited liability companies, created *ad hoc*, co-operation in the provision of machinery for joint use would appear to have great possibilities; and it would naturally extend to the distribution and marketing of products. Under the 'Improvement of Land Acts, 1864 and 1899,'* owners of land may, with the sanction of the Ministry, borrow money for agricultural and other improvements, and may charge the cost of the works upon the lands so improved. Among the classes of improvement comes the following:—

28. Engine houses, engines, gasometers, dynamos, accumulators, pipes, wiring, switchboards, plant, and other works required for the installation of electric, gas, or other artificial light in connection with any principal mansion house or other house or buildings; but not electric lamps, gas fittings, or decorative fittings required in any such house or buildings.

29. The reconstruction, enlargement, or improvement of any of the works referred to above.

While the Ministry itself has no funds for these purposes, the 'Lands Improvement Company's Act, 1920,' authorises that company to make the necessary advances in respect of sanctioned improvements. Thus a tenant farmer can borrow money in this way and repay it (over a period up to forty years) in increased rent. An owner of land can also obtain a loan at reasonable rates under the 'Agricultural Credits Act, 1923.'†

The old agricultural saying may here be parodied: you can take a farmer to the loan office, but you can't make him borrow. It is necessary first to popularise the use of electricity, and to induce a prominent man here and there to show the way, before others will follow.‡

Although the commercial advantages of electro-farming lie in power applications and in lighting farm buildings, experience suggests that the most promising line of development will be lighting in the home, with merely 'service lights' in other buildings at first,

* See Leaflet No. 59 of the Ministry of Agriculture and Fisheries (March, 1926).

† *Electro-Farming*, July, 1926, p. 60.

‡ The writer hesitates to draw a parallel with the Indian 'ryot,' who often utterly declines to use specially developed Pusa seed corn, or a Government bull, or to allow a well-bred cock among his miserable hens—which sell for sixpence and are not worth it. But the parallel seems to be there, nevertheless.

coupled with such small domestic power appliances as clothes washers, flat irons, vacuum cleaners, etc.; advancing thence by degrees to small and then large farm motors and the other applications discussed above. Some of these latter make a decided appeal to the pocket, especially in dairy and poultry work.

It has been made clear above that in the end the consumer—the farmer here—must, either directly or indirectly, and either by cash or deferred payments, meet the cost of electro-farming; either in the form of interest and amortisation of loans (§ 1014) or increased cost of energy where the undertaker either supplies the capital or collects the capital charges in this form. Assuming, as has been done, that the supply is from the National grid, and not from an isolated station, it is fairly certain that the supplier will not advance the capital directly; though a supply company formed specifically for an agricultural community might do so in order to encourage the farmers to spend more on motors and power-consuming apparatus, and thus improve the load factor and output of the station.

It is hard to avoid the conclusion that the cost of energy in rural districts (in the absence of a subsidy) must be higher than in towns, owing to the incidence of the capital charges due to relatively long lines, to the losses in these and in the various transformations (two at least, between 132 kV and the farm lines), and to the relatively poor load factor during the educational stage.

A point to be remembered is that if certain consumers combine to pay the whole or a part of the cost of bringing power to their neighbourhood, in a lump sum, then others who subsequently elect to use the power should refund a share of that cost *pro rata* in one way or another—as is now often done when an overhead service line, put up for one consumer, is pressed in to serve others.*

860. Tariffs for Agricultural Supply.—The assumption is made, in the preceding paragraph, that the capital necessary for farm electrification would generally have to be found by some other means than those of the farmer; who would then either have to repay the loan with interest in the ordinary way (§ 1014) or by an increase in the cost of his energy—with a guarantee that he would *either* consume enough energy *or* pay the balance due in

* For some obscure reason there is great opposition to this eminently reasonable proposition on the part of some suppliers—at least, in India.

the former way. In the last alternative, the tariff for energy would have to include something of the nature of a hire-purchase addition; not necessarily (or perhaps ever) paid into the coffers of the undertakers supplying the energy, but hypothecated to the body lending the capital. In this connection Chapter 11 (Maximum Demand, Load Factor and Diversity Factor) and Chapter 12 (Electricity Costs and Tariffs) should be read.

While it is useless to dogmatise as to what form of tariff should be adopted, it is quite clear that there cannot ordinarily be anything of the nature of separate different rates for 'light' and 'power'; though in point of fact this distinction has been used in Denmark,* where there is a unit charge combined with a fixed rate either per lamp, or per H.P. installed, or according to the rateable value (§ 273) or the acreage. Two-rate meters may be found useful, but two separate meters are intolerable. Despite the description given in an Act of Parliament † of a method of 'determining the fixed kilowatt charges component and the running charges component,' the reason for tariffs based on maximum demand is (like the therm) still a closed book to the layman. Nevertheless, until further experience enables the average conditions in any area to be forecasted with sufficient accuracy, an agricultural tariff for energy ought to take into account in some way both maximum demand and load factor. Mr. Matthews, ‡ speaking of the various 'seasonal' motors, etc., installed, says:—

'Since each of these will be in use only for a short time each year, it is unfair to base the tariff on the connected load. It should rather consist of a fixed charge based on an integrated, or average, maximum demand and a low rate per unit. This encourages the farmer to use one motor at a time instead of all at once.'

This, he points out, can be automatically effected by his system of restrictive switch control, whereby the load cannot exceed a definite amount. Alternatively, and perhaps preferably, a contract demand meter can be used, which only records units used above the maximum demand, which are then charged at a higher rate per unit. These meters should be so arranged as to light a lamp when the maximum demand is exceeded. There are also now several 'change-circuit' or 'load-leveller' systems available on the market.

Assuming a meter to be installed to measure the H.T. supply

* V. Faaborg Andersen, *loc. cit. supra*.

† The Electricity (Supply) Act, 1926, seventh schedule.

‡ *EZ. Rev.*, Vol. 99, p. 183.

to each farm, the losses in this are rather a formidable factor in the problem. On a 5 000 V circuit these losses will hardly be less than 100 W continuously, whatever the size of the installation. Owing to this and the losses in transmission and several transformations, coupled with low-reading errors of the meter on light loads, only one-half, or perhaps one-third, of the units (kWh) generated may be actually utilised in scattered districts. The meter losses are not registered by the meter, but fall on the supplier by law.

The basic problem of cheap rural supply is that of encouraging consumption while at the same time obtaining a good load factor. In this work the demand is very irregular, both during each day and from season to season, which complicates the tariff problem. While it might be possible to frame an elaborate tariff, taking all the factors into consideration, this would beyond doubt arrest development; simplicity is essential. Tariffs based on an annual charge per kW of maximum demand, or per H.P. installed, plus a small unit charge, are very commonly employed in other industries, and prove on the whole very satisfactory; but, though the eventual cost in terms of pence per unit obviously decreases with every additional piece of apparatus installed, the fact remains that the minimum fixed charge is often a bone of contention and the unit charge a deterrent of consumption. From the point of view of popularising the use of electricity in every department of the farm—and perhaps from the supplier's angle also—it is doubtful whether any better scheme can be evolved than a plain contract price per annum, per H.P. of maximum demand, with unlimited use.* This system has the advantage that the farmer realises that he is paying for electrical service in the broadest sense, and can get free and indefinite overtime out of it. Basing the cost on the maximum demand would in time ensure that no unnecessary overlapping of loads would take place; and things that could be done at any time (like water heating and corn grinding) could be used to fill up the hollows and raise the load factor.

The farmer who is using his own motors and lamps is not likely to use them to excess, even though it costs nothing in

* If ploughing and other cultivation is the main application, it might be better to settle upon a price per acre per annum; for a dairy farm, so much per stall or per head of stock per annum, and so on—but always without restriction in use for all subsidiary applications. But systems requiring local inspection are not to be recommended.

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energy, because of wear and tear. On the other hand, he *will* use the energy freely, and thus get good service and a good return for his money. With a unit charge he worries about running up his bill, cuts his benefits, and in the end pays nearly as much as the contract charge for far less service.

If a comparison be made between a contract charge and a fixed charge plus low price per unit, it will be seen that the former safeguards the supplier, while favouring the customer, and encouraging free consumption and the use of portable motors for miscellaneous jobs. Thus take, on the one hand, a contract price of £10 per H.P. year = £13·40 per kW year of maximum demand and compare it with a fixed charge of £5 per kW of M.D. plus $\frac{1}{4}$ d. per unit, as in Table 188.

TABLE 188.—*Comparison of Tariffs for Agriculture.*

Average Use for 350 Days of	Units.	Contract Rate.	Fixed Rate plus Unit.		
		£13·40 per kW Year.	Units.	$\frac{1}{4}$ d. + £5. Total	Pence per Unit.
2 hours	700	4·6d. per unit	£ s. d.	£ s. d.	
4 "	1 400	2·3d. "	2 3 9	7 3 9	2·45
8 "	2 800	1·15d. "	4 7 6	9 7 6	1·6
16 "	5 600	0·58d. "	8 15 0	13 15 0	1·18
			17 10 0	22 10 0	0·96

A difficulty which occurs in this connection—and which would occur with any other tariff scheme—is that of the heavy seasonal demands for ploughing and (in a lesser degree) thrashing. With rope-haulage ploughing—whatever may be the case with tractors—there would not be ploughing on one estate for many days in the year, and the load of at least 20 H.P. and often from 50 to 100 H.P. would yet govern the contract price for the whole year. The only obvious solution of this difficulty is an extension of the co-operative buying of such plant as suggested above (§ 859), *i.e.* a group of farmers, having purchased an outfit for their joint use, would pool their contract demands at least during such time as the outfit is in use. Such an arrangement demands a measure of co-operation not evident in the past, but one which may justify by its commercial advantage the strain which it imposes on

human nature. Without co-operation, electro-farming is well-nigh impossible.

So ingrained, however, is the policy of charging something for each unit, that it may hold the field. In that case it may, as a matter of policy, be advisable to include a consumption up to a certain point (according to the size of the installation) in the fixed monthly or quarterly charge, and then to charge a low rate for all units *in excess*. For example, with an installation having a maximum demand of 3 kW, the charge might be 3s. per kW of M.D. altogether for the first 24 kWh (*i.e.* 8 units per kW of M.D.) and then 1½d. per unit thereafter. The net result of this would be the same as a charge of 2s. per kW of M.D. plus 2d. per unit for *all* units.

861. Bibliography.—(See explanatory note, § 58.)

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Rural Electrification and Electro-Farming (Electrical Press).

Special attention may be called to the articles continually being published by Mr. R. Borlase Matthews, a Chartered Electrical Engineer, who is also a practical farmer. His work in electro-farming at Greater Felcourt Farm, East Grinstead, covers all phases of the applications of electricity to agriculture, the treatment and handling of the crops, and the administrative organisation.

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Much useful information may also be found in the papers read before the American Society of Agricultural Engineers and in the Reports issued by the United States Department of Agriculture, and the Bulletins of the Committee on the Relation of Electricity to Agriculture.

Valuable service is being rendered to electricity in agriculture and to rural electrification in general by the Overhead Lines Association (Secretary: G. W. Molle, 32 Shaftesbury Ave., Piccadilly Circus, W. 1).

NOTE (Addendum to footnote †, p. 488).—At the time of writing (1933), it seems probable that the use of carbon tetrachloride fuses (§ 375, Vol. 1), instead of circuit-breakers, will contribute greatly to the extension of electricity supply in rural districts by cheapening the cost of tapping the national 'grid'. Tests on 132-kV fuses of this type show that a short-circuit exceeding 900 000-kVA can be cleared with certainty; while 11-kV fuses are designed to clear a 100 000-kVA fault. The cost of the fuse equipment is only a fraction of that of a circuit-breaker for similar duty.

CHAPTER 34.

ELECTRIC TRACTION; SYSTEMS, ROLLING STOCK AND POWER.

BASIC MERITS AND PROBLEMS OF ELECTRIC TRACTION.

862. Introductory.—The whole question of tramways, and of electric traction on tramways (known as ‘street railways’ in America), is approaching the point where one may cry ‘The King is dead; long live the King.’ For although, like Charles II., tramways are ‘an unconscionable time a-dying,’ they are being steadily pushed towards that inevitable goal by the pressure of other and more flexible vehicles. Meanwhile the electrification of railways has become practical politics and, to some extent, an accomplished fact. So far, all old underground lines have been converted to electrical working and all new ones are built for it; suburban lines are now following, and must continue to do so around all the great cities, in order to cope with the ever-increasing urban population; many mountain railways have been electrified, and all are certain to be in the near future, seeing that they can almost invariably utilise—and regenerate—hydro-electric power. Main lines will follow in due course, and many of those abroad have shown the way, including the 850 miles of the Chicago, Milwaukee and St. Paul Railway; branch lines will be last, *longo intervallo*.

Not only passenger traffic but goods traffic will be so carried in the end, with a great saving in rolling stock owing to enhanced speed; and goods traffic is the key to the railway cash-box. The essence of the whole problem is not technical but financial, and with this aspect we cannot here deal adequately.*

Electrification will also before long become an economic necessity, both for relieving the present congestion at termini,

* See ‘The Financial Prospects of Railway Electrification,’ by Sir Philip Dawson; *Electrician*, June 1, 1923, p. 594.

and the bottle-neck approaches to them, and for conserving dwindling coal supplies (§ 863). A minor point, though worthy of mention, is the improvement in health resulting from electrification. This obviously follows when underground lines are considered, but it is also true of surface lines, especially those with many tunnels, and particularly as regards the running staff, who are comfortably housed and free from dust, coal gas and draughts. Already the lines passing through the Alpine tunnels—the St. Gothard, the Simplon, the Loetschberg, etc.—have adopted electric working.

The importance of the whole subject is such as to call for more detailed treatment than was meted out in earlier editions, though, even so, specialist treatises must be consulted on details (*see Bibliography*, § 934). Road vehicles, as previously, have a chapter to themselves in this volume, while haulage in mines is briefly dealt with in the chapter on ‘Electricity in Mining.’ In this chapter and the following one we deal with electric tramways and railways. In general principles, what applies to the one applies also to the other in the matter of power calculations; of the supply of energy to the system; in the application of that energy on the car or locomotive; and in the generation and transmission of the energy from its source to its ultimate destination. The differences are in degree rather than in kind. Far greater loads have to be carried by railways, especially by goods trains, which are mainly responsible for the revenue earned*; higher speeds are demanded by both express and passenger trains, while the speeds of goods trains (which have to be fitted into the time schedule) is more comparable with tramway speeds, and need accelerating; and, in consequence of these two, there is a much greater energy demand from the power house to the track and from the track to the motors in the case of railways. Furthermore, there is still, and there will for many years be, the problem of carrying both steam and electric trains on the same track, with the result that the transmitting medium (whether third-rail or overhead) has to cope with smoke and cinders†; but this may be offset in street tramways by the equally objectionable mud and

* Up to more than 90 % in some cases.

† Sulphur fumes have been known to rust the newly-laid third rail in a tunnel, so that trains were stalled on the first day of working.

slush in which our climate specialises, modified to some extent by the disappearance of the horse-drawn vehicle. In both cases the slower moving traffic interferes with, and slows down, the ideal schedule of the electric service.

863. Savings Due to Electrification.—The electrical engineer is in these days prepared to convert any line to electrical working with perfect confidence in the technical results; but the business man wants to know what the nett saving will be to his line. It is clear that the more traffic a line carries, up to what would be the saturation point of congestion with steam working, the greater must be the percentage saving.

From the National point of view, the conservation of coal supplies is of immense importance, and has been largely responsible for the schemes of the Electricity Commissioners; when these are further advanced the problem of power supply for railways will be largely solved. It has been calculated that the complete electrification of British railways would alone save seven million tons of coal per annum.* In view of the coal situation this is important enough, though of course capital charges for electrification—especially for cables and transmission—must be set off *per contra*; and the effect of saving coal on the cost of miners' unemployment must not be left out of account. American experience proves that where trains are heavy and gradients severe—in both of which respects American conditions are stiffer than British—electric locomotives have a considerable advantage both in actual capacity for doing the work and for doing it economically. As an example, the savings directly due to electrification on the Chicago, Milwaukee and St. Paul Railway† are worth attention. Hydro-electric power is used, and a comparison was made between actuals on the same line for both methods of working. For 1923 the gross ton-miles carried, freight and passenger, amounted to just under 3 000 million (short) tons, showing a saving (based on the last year of steam working) of over 1½ million dollars. This takes no account of the possibly increased revenue due to the release of

* From a modern power plant a coal consumption of about 2½ lb. will produce 1 H.P.-hr. on the wheels of an electric loco, whereas a steam loco uses about 6 lb. for the same production of energy. See § 894.

† *Power Plant Engineering*, March 15, 1925, p. 364.

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rolling stock used for carrying coal* or any other indirect effect.

In countries with supplies of inferior fuels, which can be burnt satisfactorily in power stations but not in steam locomotives, there is a powerful argument for electric traction (§ 919A).

On one of the main British railway groups the average mileage per steam locomotive is 26 000 miles per annum for passenger and 18 300 for freight engines, and the cost of engine repairs per engine-mile averages 5·8d. The analogous train mileage on the electrified suburban lines varies from 36 000 to 47 000 miles and the cost of repairs varies from 2·1d. to 6d. per train mile, with an average of 4·18d. The density of traffic on these latter is about 20 000 train-miles per track mile per annum.†

864. Classification.—Several methods of classification may be adopted in considering the problems of electric traction, though, whichever may be preferred, the treatment of the subject cannot follow any one of them without over-lapping.

In the first place, there is, in this country at any rate, a clear distinction between a tramway and a railway—with the ‘light railway’ intermediate—though in America no such distinction is made, and the inter-urban street railway bridges the gap; in most cases these are dealt with in separate paragraphs. Railways proper may be further sub-divided into main lines and local lines (§ 865), and the latter again into urban and suburban lines. In nearly all cases there are both passenger and goods services.

Secondly, there is D.C. traction and A.C. (3-phase or single-phase) traction, each with a considerable range of variation in such matters as pressure and frequency (§ 868), and each applicable to most of the varieties enumerated above.

Thirdly, the nature of the vehicles may be considered, whether self-contained (§ 873) or drawing power from an outside source; the latter including tramcars (§ 870), motor coaches (§ 871), multiple-unit trains, i.e. trains made up of several motor coaches all operated from one by means of a master controller (§ 871), and locomotives (§ 872) drawing power from a central station.

Finally, there are a number of methods by which power may be

* On some American lines nearly one-fifth of the total ton-mileage consists of coal carried for use on the line.

† ‘The Future of Main Line Electrification on British Railways,’ by Lt.-Col. O’Brien, D.S.O., *Jour. I.E.E.*, Vol. 62, p. 729.

conveyed from the stationary conductors to the moving vehicle. Of methods which need merely be mentioned, there is the conduit system,* in which both the conductors (lead and return) are carried on insulators in a slotted conduit reached by a plough, and the surface-contact system in which studs flush with the roadway were used to convey current to a collecting skate on the car as it passed over them, but were alive at no other time. The latter system was killed by rain and mud.

Only the two chief systems which have survived are dealt with here, *viz.*, the overhead or trolley-wire system (§ 909 *et seq.*) and the third-rail system (§ 920 *et seq.*). The relative merits of these two may be briefly referred to here. The overhead system has the advantage of not in any way interfering with the maintenance of the track and the safety of platelayers, whereas the third rail is not only a potential source of danger but also forms an obstruction to the proper packing of railway sleepers—it is, of course, not used on tramways. Also the third rail is easily wrecked by derailments, and the gaps necessary at level crossings, points, etc., may cause a locomotive to be stalled in case of an emergency stop.† On the other hand, overhead equipment is an obstruction to the working of breakdown cranes and involves the use of a tower wagon for inspection, which occupies the line; while the third rail is readily accessible, but must have the current cut off from it before repairs can be carried out. Broken collector shoes are not unknown, and cause short-circuits at all points and crossings through the bus connecting all the shoes. Seventeen such shorts occurred in rapid succession at one substation.

865. Main Line and Local Traction on Railways.—In the United States there are still many growing townships with sparsely populated country in the stretch between them, so that the useful cross, half A.C., half D.C., between a railway and a tramway known as an 'inter-urban street railway' performs a very necessary service. In this country there is but little scope for such a system, and what there may have been has now disappeared with the triumph of the motor omnibus and coach. But apart from

*The conduit system is still in use in various places, including London, where its adoption was inevitable owing to the attitude of the local authorities concerned.

† Without any emergency, other than a signal at danger, electric trains running through the bottle-neck into Waterloo (London) get stalled occasionally at such dead spots.

the considerations of weight and speed mentioned in the previous paragraph, there are wide differences between what is suitable for long non-stop runs (passenger or freight) on main lines and what will serve for urban or suburban traffic with frequent stops. In the former, rapid acceleration and deceleration, which have a potent influence on the design of the motors and on the demand on the power-house, are of negligible importance; in the latter they are the predominant factor, for braking often begins within a few seconds of acceleration ceasing, and the intervening seconds are mostly spent in 'coasting,' *i.e.* running by momentum with the power cut off. A main-line express, having reached its determined speed, may have to carry on at full power for perhaps 50 miles or more to maintain that speed, so that the time spent in starting and stopping is of no moment. With short runs and frequent stops the full-running time is unimportant, the running to schedule and the daily capacity of the line depending on the time lost at stopping places—including signals every hundred yards in bottle-necks. Accelerations up to $1\frac{1}{2}$ and $1\frac{1}{2}$ m.p.h. per sec. or more are obtained on suburban and 'tube' lines in practice—the average on the former is about 1·2 m.p.h. per sec.—whereas with steam locomotives it is of the order of 0·5 m.p.h. per sec. An obvious corollary is that whereas the entrances and exits on main-line coaches may be of the stereotyped design, those on suburban and 'tube' coaches must be designed with the view of being emptied and filled in the minimum time.

As regards main-line electrification generally, the following extract states succinctly where competition with steam becomes practicable:—

Steam traction can handle efficiently and at reasonably low costs, both for operation and fixed charges, a train service of heavy trains even at fairly short headway with stops not very close together. With few stops and an irregular and infrequent train service electric traction cannot show much superiority in operating characteristics; but if the stops are at short distances apart or the service demands great flexibility in seating capacity to meet widely varying passenger numbers, the operating conditions then demand two features which electric traction can give: (1) high acceleration; (2) multiple-unit train formation.

Where the operating conditions, *i.e.* the requirement of traffic, are such as to make these demands, electric traction is the proper means of adequately meeting these requirements, and it then remains to investigate the financial aspects of the change (H. W. Firth, *Jour. I.E.E.*, Vol. 52, 610.)

Experience indicates that the prospects of main-line electrification schemes are often more favourable than represented by the

above excerpt. Much useful information concerning the practice and experience of America is to be found in the 'James Forrest' lecture presented to the Institution of Civil Engineers by H. M. Hobart so long ago as December, 1915. (See examples of suburban lines in paragraphs 915, 916, and 921 and of a main line in paragraph 918.)

A further point of importance, indicated in paragraph 862 above, is that of terminal congestion, especially in connection with suburban services at the rush hours. Many of the delays on our railways are due to the impossibility of clearing the track in stations and in the bottle-necks so commonly found just outside them.* The substitution of electric trains more than doubles the capacity of a terminal station, both because of the high acceleration and the double-ended operation possible; and the former property assists the rapid passage of the narrows.†

As regards *freight traffic* Sir Vincent Raven some years ago‡ showed the advantage to be obtained from electrical working in a particular instance. For the same ton-mileage there was a reduction of 25% in train mileage and a decrease in the time of a through journey from 56 hrs. to 26 hrs. The saving in new rolling-stock directly traceable to this saving in time amounted to 423 forty-ton waggons on a line handling 13 000 tons a day, and the number of locomotives could be about halved. The capacity of the line was increased by 35% by the change. It has already been remarked that finance is the essence of the problem of railway traction, and this is a good example. The capital spent on building a line is enormous, even leaving aside such abnormal cases as the million-pound-a-mile semicircle between Charing Cross and Cannon Street; and what may be termed the traffic load factor—or ratio between the number of trains actually on the line and the number which could be accommodated if every block were occupied—is of the first importance. This ratio can be increased by shortening the block sections, by the installation of modern electrical signalling (§ 933), by increasing the acceleration on the trains, by running

* It seems obvious that sooner or later the approach from Vauxhall to Waterloo must, for all suburban traffic, be carried either by 'tube' below the main line or by elevated railway above it.

† 'The Financial Prospects of Railway Electrification,' by Sir Philip Dawson (*Electrician*, June 1, 1923, p. 595). See also paragraph 921.

‡ *El. Rev.*, Vol. 88, p. 907.

smaller trains at less intervals and by losing less time in terminal shuntings and engine reversals. Furthermore, every idle wagon is so much capital earning no revenue.

THE SUPPLY AND UTILISATION OF POWER FOR TRACTION.

866. Systems of Supply for Traction.—Before discussing the merits and demerits of D.C. and A.C. in connection with traction problems the position generally may be surveyed. Either D.C. or single-phase or 3-phase A.C. can be used for traction (§ 868). Most electric tramways are worked with D.C. series-wound motors (§ 676) at a pressure of 500 V, with current from over- or under-compounded generators (§ 138) at a pressure of from 500 to 550 or 600 V; if the main supply is obtained from an A.C. plant, rotary-converters (§ 408 *et seq.*), motor-converters (§ 413), motor-generators (§ 388) or mercury vapour rectifiers (§ 422) are employed in substations (§ 869) to feed the line with D.C. In some cases single-phase A.C. motors are used on the cars; in this case the line and motors may be fed from transformers or direct from the generators at 500 V or thereabouts, or (more often) a high-pressure supply on the line is transformed down to low-pressure on the cars themselves, and low-pressure motors are used. The line may either be fed from a single-phase generating station; or from converters working off a polyphase main supply; or from a 3-phase system transformed to 2-phase (§ 394), the two phases being independently used on separate sections of the line. Finally, 3-phase motors may be used on the cars, in which case three conductors have to be used on the line, which is fed from 3-phase transformers or directly from the generating plant; there may either be three insulated trolley wires or two such with the rails for the third, and either high-pressure or low-pressure motors may be employed. Whatever motors are employed, it is essential that they shall have a high starting torque, so that they may be capable of starting under all conditions of road and gradient and of giving rapid acceleration. On electric railways, pressures of 1 500 to 3 000 V D.C. are often used on the motors.*

* See 'Final Report on the Electrification of Railways,' by the Advisory Committee of the Ministry of Transport. While agreeing that existing systems should be allowed to remain and, if necessary, be extended, the Committee recommends D.C. at 1 500 V for future work; or, alternatively, multiples or sub-multiples of that measure.

During recent years the popularity of D.C. supply for traction purposes has been greatly increased. London 'tube' and suburban railways are mostly operated on D.C. at 600 V, distances being comparatively short and through-running facilities being important. Higher pressures will doubtless be used in most inter-urban and main-line D.C. schemes undertaken in future. Valuable experiments—not very successful—were conducted with overhead supply at 3 500 V D.C. on a short section of track between Bury and Holcombe Brook, and the third-rail system with supply at 1 200 V D.C. has been adopted in initiating a comprehensive electrification scheme in the Manchester district. An alternative system is to supply A.C. to the conductors over the track, and to convert the energy to D.C. on the loco itself. On the Michigan Traction Company's experimental line, motor-cars have been used, each with four 100 H.P., 2 500 V machines of the double-armature type (1 250 V on each armature). These motors work in pairs on 5 000 V D.C. obtained from steel-clad rectifiers (§ 423) carried on the motor-car. The current for given power is only about one-eighth as great at 5 000 V as at 600 V, and experience shows arcing at the collector gear to be less serious at the higher pressure though the danger of flash-over is increased. Assuming 85 % motor efficiency, 400 B.H.P. corresponds to about 70 A at 5 000 V or 590 A at 600 V.

In a 'James Forrest' lecture presented in 1915, H. M. Hobart arrived at the conclusion that high-pressure D.C. locos were an established success, and that the D.C. system was the most suitable for main-line electrification (as well as for suburban work). The cost of supply at the locomotive is about the same for high-pressure D.C. as for 25-cycle, single-phase A.C., but supply converted from 60 to 25 cycles in substations costs more and involves the use of frequency-changers (§ 390), which means sacrificing the simplicity of static substations. Single-phase locos cost more than D.C. locos, and the efficiency of the single-phase system is lower.

867. A.C. versus D.C. Generation and Transmission for Traction.—*Generation.*—The relative merits of A.C. and D.C. generally have been dealt with in many places in these volumes, but every application of power has its own special problems in this connection. With respect to generation for traction, the problem has practically solved itself in this country; where D.C. generating stations with compound-wound 550 V dynamos have been built for supply to electric tramways alone, they will carry on until they are scrapped for economic reasons—a process which, in less conservative countries than Great Britain, would have culminated years ago in most instances. New generating stations are unlikely in future to be built for such a restricted service as tramways; but, if they are, they will almost certainly generate A.C. whatever the nature of the motors to be served. There is still, however, likely to be a demand for special tramway generating plant for the Dominions and abroad.

For electric traction generally, and for railways in particular, as indeed for nearly every other service except electrolysis, A.C. has definitely triumphed in the matters of generation and transmission

to the point of use. The advantage of being able to use high pressures and small copper sections is supreme, whether the energy is ultimately to be converted to low- or medium-pressure D.C. or not, and whether the line is main, suburban, urban or tramway. Furthermore, so far as Great Britain is concerned, in nearly every future instance the energy for this service will merely be a part of the load of a 'selected' central station (§ 1041) laid out for the general interconnected supply of a large district, and situated where the conditions are most favourable for obtaining land, condensing water and a railway siding—proximity to the centre of gravity of the load being always subsidiary to these crucial conditions, especially so where the station is one of several feeding the same network of mains. Some of the existing stations, built exclusively for railway service, may prove good enough to serve as 'selected stations' of the National system—provision is made for this in the Electricity Supply Acts (§ 1041)—but it is doubtful whether those responsible for main-line electrification in the future will even wish to generate for themselves, in view of the greater security of the interconnected public systems.

Where hydro-electric power is commercially available, as is generally the case in America and on the Continent, it will naturally be used.

Finally, the portable generating station, carried on the train, may be mentioned. Recently British and Swiss firms in association built some travelling power-houses employing Diesel engines to drive generators (*see* § 873), which in turn drive the motors on five-coach trains—including similar motors on the travelling station itself. The method seems roundabout (as well as 'gyratory'), but no doubt the conditions in the Argentine, where the equipment went, justified it. The high thermal efficiency of the Diesel engine gives it an advantage over the similar steam-electric travelling power-houses occasionally tried. Much experimental work in regard to Diesel-electric trains and motor coaches has also been done in all the principal countries (§ 873).

Transmission.—Power having arrived in the neighbourhood of the line to be served, in the form of standard E.H.T. 50-cycle A.C., transformation and / or conversion to the form required on the line will take place either in substations (§ 869) owned and operated by the traction authority, whether it owns the generating station or has purchased the supply, or on the locomotives them-

selves (§ 919A). Thus, for example, the suburban lines of the Bombay, Baroda and Central India Railway (of which further mention is made in connection with overhead equipment (§ 915) derives its power, at 22 kV, 50 cycles, from the Tata Co.'s main receiving station, to which it is delivered at 100 kV by the hydro-electric transmission lines. The railway supply is re-transmitted from the main receiving station, at 22 000 V between phases, to the substations, which convert it to 1 500 V D.C. for the overhead track line. The 22 kV lines are carried on extensions of the steel structures (Fig. 405 in § 915) supporting the contact wire equipment, as also is a 2 200 V 3-phase line used for subsidiary purposes such as station lighting and signalling.

868. A.C. versus D.C. Systems on the Line and Rolling Stock.—Both A.C. and D.C. at various pressures from 500 V upwards have been and are being used for operating purposes, as well as the combination of the two on the same vehicle.

For *tramways*, the use of D.C. at 500 V is fairly universal, whether obtained from the power-house in that form or from converter substations. In *railway* work, practice has not yet crystallised. For urban and suburban lines with frequent stops and rapid acceleration D.C. has generally been used, as the series motor with series-parallel control has no rival for such a service. But while 500 V is considered the safe limit for vehicles running on the ordinary public roads, there is no need for such restriction where the line has its own track, either over or underground; and the tendency is to standardise D.C. at 1 500 V for such lines (§ 866 footnote). The power demand on such a service as is given by the London tube railways (worked at 600 V only) involves very heavy currents, and the saving in copper made by raising the pressure would be very great. On suburban lines the density of the traffic, though very considerable, is far less than on urban tubes; but the runs are longer, and 1 500 V is more economical than 600 V, now that the original difficulties with 1 500 V rotaries have been overcome.

The future of A.C. for the actual operation of traction systems is unsettled. Although often used for the outlying sections of American street railways—corresponding to our tramways—it is unlikely that A.C. will be adopted for a corresponding service in this country. On urban and suburban lines with a private track it is also unlikely, so far as can be foreseen, that A.C. will be used,

because the characteristics necessary for the service—discussed above—are lacking. Single-phase A.C. at 1 500 V was adopted on a section of the Brighton line (§ 921) some years ago, with overhead construction, but since the merging of the railways into a few groups the advantages of interchangeability of rolling stock on a standard system have become more apparent; and there seems little doubt that the D.C. third-rail system used on more recently electrified lines of the Southern Railway, and now displacing the single-phase section, will be the final selected system for this class of service on other lines also.

Main-line electrification has not yet advanced far, though there are examples abroad and in America (§§ 918 *et seq.*). In Great Britain it will certainly be undertaken sooner or later, but the ultra-conservative directors of the various lines are not yet satisfied that the heavy capital expenditure is justified in view of the general position, on grounds rather political and industrial than technical. Consequently it is impossible to forecast what system will be used in the end, though it is probable that a single system with complete interchangeability will be agreed upon beforehand or enforced by legislation on all the groups of railways. For these main lines, A.C. is perhaps more likely to win through than D.C., chiefly because it is possible to transmit at high pressure right on to the locomotive or coach, and then to transform down to a safe working pressure on the motors and control gear. With D.C., a pressure higher than about 3 000 V would offer difficulties; but with A.C. there is no reason why the vehicle should not collect power at 15 000 V and yet use 500 V motors. It is unlikely that single-phase A.C. will be used in future for this service, as 3-phase motors are in every way more suitable when once the difficulty of collecting from the larger number of overhead wires, and the consequent difficulties at cross-overs, etc., have been overcome to the satisfaction of the Government Department concerned.

869. Substations.—As recorded elsewhere in this volume (§ 1041), the reorganised National supply of Great Britain will eventually originate in a comparatively small number of power stations, interconnected by a network of 50-cycle transmission lines using extra high pressures. There are obvious limits to the pressure which can reliably and safely be collected by a moving vehicle on track exposed to the weather; and, apart from this, it is clear that the controlling staff of an electric line must be solely

responsible, and entirely independent of the central station, inside the point where delivery takes place. Furthermore, the generating authority, however large the plant may be, cannot risk the shutting down of the whole system in consequence of a railway mishap or other unforeseen event. In nearly every case, therefore, there will be substations (§ 426 to 428, Vol. 1) belonging to the traction authority along the line; to these power will be delivered, and from the point where it is measured the traction authority will have full control, though the suppliers will be able to ensure that they are safeguarded, on their side of the point of transfer, from abnormal demands beyond the inevitable short-circuits that occur from time to time.* At present most substations in this country are served by incoming and outgoing underground cables, but in future it is probable that overhead lines will be used—as they are now abroad—to a far greater extent. Lightning and surge protection are required; transformation from the supply voltage to that needed for the line or the converters (as the case may be) will be effected;† a switchboard will control the incoming and outgoing circuits; and the necessary protective gear and measuring instruments will be installed. If A.C. is hereafter used on main lines from beginning to end there may be a considerable opening for outdoor substations (§§ 381, 427).

Where D.C. is employed, as it is likely to be in Great Britain, the protection of converters from damage due to flash-over on short-circuit has necessitated the evolution of the modern high-speed circuit-breaker; see § 372 (3), Vol. 1 (5th edition).

Until recently the D.C. side of converters was generally built for 750 V and two were put in permanent series for 1 500 V, but 1 500 V rotaries are now becoming standard. For reasons given in § 372 (3) ('High-speed circuit-breakers') modern traction rotaries incorporate special features for obviating destructive flash-overs. Special fans are included in the machines for producing a draught strong enough to remove all ionised air from the commutator; and all parts to which an arc is likely to strike

* As a corollary to severe short-circuits, copper vapour will often make an appearance; and the uncanny property of this vapour for starting arcs over large distances, even with quite low voltages, has led to modifications in the design of machines, switchgear, and traction equipment generally.

† On the G.I.P. Ry. (§ 916) transformation from 100 kV to the converter pressure is effected in one stage.

are shrouded with arc-proof insulating material, almost to the extreme of interfering with the ventilation. Some rotaries known to the authors show a tendency to flash-over to the inside of the armature spider, presumably owing to eddies carrying ionised air there, so that now the spider is completely blocked off with an insulating barrier. Again, the commutator is now made of the same diameter as the armature, so as to increase the spacing of the brush arms and, more important still, to eliminate the 'riser' connections between the commutator and armature, which were always liable to come together and produce short-circuits independently. In acceptance tests the last short-circuit has been specified to take place with the high-speed circuit-breaker rendered inoperative, showing that modern traction rotaries are intended to be flash-over proof on the strength of their own design. In this test, the circuit is broken by the ordinary circuit-breaker (0.5 second) on the A.C. side. The advent of the 132 kV lines of the Electricity Commissioners necessitates transformers with that primary pressure, which have hitherto not been built in this country. Outputs are also increasing, and 54 000 kVA transformers have been built for Buenos Ayres consisting of three 18 000 kVA single-phase units with one spare.

Mercury vapour rectifiers (§§ 422, 423) are now able to compete actively with other converters in the service required for traction, or to co-operate with them in parallel working. As already recorded (§ 423), ironclad rectifiers have been made up to a capacity of 3 750 kW at 5 000 V and the limit is by no means reached. Requiring less attention, they will probably displace converters altogether in the end. Mercury vapour rectifier substations for general service are in use in Birmingham and are largely used abroad, and for traction work they are already employed. No motor-generator or convertor can compete with them for high-voltage D.C., and higher pressures than the present 1 500 V are certain to be used presently. Large M.V. rectifiers, however, have to be provided with motor exhausters and cooling water supplies, so cannot be left altogether to themselves.

To what extent the transverter (§§ 414, 425) will eventually come into the picture remains to be seen. It offers extra high tension D.C. for transmission and any standard medium pressure at substations.

Automatic Substations.—Automatic and semi-automatic sub-

stations (§ 428) have already been used to some extent in traction service, and are destined to play a very important part in future. In his 'Review of Progress' of electric traction* (1927) Mr. F. Lydall distinguishes between the 'full automatic' and the 'supervisory control' automatic substations:—

The central idea is that when the conditions of loading require it, the converter or motor-generator is started up and switched on to the line; when the supply is no longer needed, the set is switched off and disconnected; and when anything abnormal occurs either on the line or in the substation, the set is automatically protected either by a temporary opening of the feeder circuit-breakers or by shutting down and locking the set out of action until an inspector has visited the substation and dealt with the trouble. Under normal operating conditions the starting of the set is governed by the line voltage, so that when the local demand is such as to reduce the voltage by a predetermined value below the normal pressure, the set is run up and switched on to the line. When the load falls off, the controlling relays open the main switches after a definite time interval, and the set is disconnected from the line and stops.

This type of automatic or unattended substation is generally referred to as being fully automatic. Other systems have also been developed, known as supervisory control systems, in which all such operations as starting and stopping the sets, connecting them to the bus-bars, opening and closing feeder circuit-breakers, are carried out by a supervisor by remote control from a central point or from a neighbouring substation. Subject to such remote control the working of all the switchgear in the substations is entirely automatic, complete safeguards being provided to protect the machines against injury due to breakdown or faulty operation. The supervisory system usually makes provision for back-indication, *i.e.* indicating to the supervisor whether the switching operations he has initiated have been properly carried out and completed and showing also the opening of any switch due to overload or short-circuit (*see* § 892).†

In the electrification of the Cape Town suburban railways the rotary converter transformers are fed at 33 000 V, 3-phase, and deliver D.C. at 1 500 V; the G.E.C. (London) all-relay tandem supervisory system of control is applied to these rotaries, enabling the load despatcher at the central station to start or stop them at each and all of the six substations and to assure himself by means of visual indications that they have done what he requires and are working properly. Automatic substations are also used on the Sheffield tramway system, and an account of their working will be found in the *Electrical Review*, Vol. 102, p. 1078.

* *Jour. I.E.E.*, Vol. 65, p. 151. *See also* § 893, below.

† For a description of the supervisory-controlled substations of the Bombay, Baroda and C.I.Ry., *see the Metropolitan-Vickers Gazette*, October, 1928.

ROLLING STOCK.

870. Tramcars Supplied with External Power.—While cars and locomotives with self-contained power (§ 873) have their special uses, the majority of vehicles of all sorts are propelled by power obtained from a central station. These comprise street tramcars, motor coaches running on railway lines, and railway locomotives. Tramcars will be dealt with first.

On British tramways, the use of trailing cars is not encouraged, though they are occasionally used for service (as distinct from passenger) work; in some countries they are used in order to have two 'classes.' Generally, however, the tramcar is a single unit, either single- or double-decked, equipped with two series-wound, D.C. motors and series-parallel control. The time has passed when any detailed description is required, improvements being mainly in the direction of non-electrical equipment and higher power. The standard gauge (4 ft. 8½ in.) is most widely used, but there are several important systems in this country using 3 ft. 6 ins., and some intermediate values. Seating capacity runs up to about 60 for a single truck, 30 ft., 10-ton car and say 90 for a bogie, 34 ft., 15-ton car. The two motors vary from 25 or 30 B.H.P. each in the smaller type up to 50 or more B.H.P. in the larger, according to the gradients met with and the length of the hills to be traversed.

871. Rail Motor Coaches and Multiple Unit Trains.—Motor coaches are also often used singly, for the same type of traffic as self-contained vehicles (§ 873); but they are generally so designed that they can be made up and operated in any number that suits the traffic of the moment, multiple control being employed by means of a master controller in the driver's cabin to operate all the motors simultaneously (§ 741).

With motors on every axle, or at least on most cars—and two or more per vehicle are almost invariably employed, in order that series-parallel control may be used—the adhesion (§ 890) is immensely increased over that obtainable with a locomotive drawing a whole train from 6 or 8 axles, and higher acceleration can be obtained without danger of skidding; if there are motors on every axle the adhesive weight is obviously the total weight of the train. In some cases each equipment consists of two sets of D.C. motors, each set made up of two armatures permanently connected in series, so as to reduce the commutator voltage.

Generally the 'unit' system is employed, a unit consisting of either 3 or 4 coaches, and 1 to 4 of these units comprising a train. The make-up of the units varies; on the Bombay suburban lines there is a driving trailer (*i.e.* a coach containing a driving position with master controller, etc., but no motors); a motor coach, provided incidentally with a driving position for convenience in repair shops; a plain trailer with no equipment at all; and another driving trailer to bring up the rear and provide for operation in either direction. (For another arrangement *see* § 916.)

This type of rolling stock is used on most of the London suburban railways, interspersed with trailers often, and also with both driving wheels and free bogies on the motor units. Trains vary, according to the time of day, from a single coach up to six or eight, with a seating capacity of 400 and straps for nearly as many more. The weight of such a train, full, is about 200 tons, and up to 2 400 H.P. of motors is required to maintain the usual schedule speed of 30 M.P.H. Westinghouse (compressed air) brakes are used in place of the vacuum brakes of British steam lines.

The motor coaches on the Morden extension (London Underground) are 51 ft. long overall, 8 ft. 6 in. wide and 9 ft. 6 in. high. One motor bogie with a 6 ft. 11 in. wheel base and one trailer bogie of 6 ft. are used, both with roller bearings. On the Sydney suburban service over 300 motor coaches, each with two 360 H.P. motors, are used.

872. Electric Locomotives.—For main-line railway work electric locomotives are for the most part used, their equipment varying greatly with the service required of them. Examples of types will be found below and in paragraphs 915 *et seq.* From two to a dozen motors may be used, with varying numbers of driving wheels, the larger types being articulated. In some a jack-shaft and side-rods, as in steam practice, are used; in others the geared quill drive is employed, the motor being aligned with the axles but connected to the drivers through springs; in others there is a plain geared axle drive; and finally there is the gearless type. Gear ratios vary greatly according to the type of service and speed required.

D.C. Goods Locomotive.—As an example of locos for heavy freight service, those on the Great Indian Peninsular Railway (Bombay) may be cited. This line is described in some detail in

paragraph 916, where further technical details of the locos are added. The line, recently converted to electric working, rises some 2 000 ft. up the Western Ghats from the plains of Bombay, with gradients up to 1 in 37, and until it was electrified there were great delays in consequence of a reversing station being required. The 'Metrovick' locos weigh 120 tons and are rated at 2 600 H.P. They are of the side-rod type, with a total length of 60 ft., the body being carried on two flexibly connected trucks each of which is equipped with a twin motor of 1 300 H.P. (For performance see § 916.)

D.C. Passenger Locomotive.—For high-speed passenger service on the same line the locos are of 2 160 H.P. Here the motors and gearing are rigidly mounted on the frame of the loco and transmit their power through universal flexible motion link drives, capable of accommodating the movement between axles and frames. By thus relieving the axles of dead-weight and keeping a high centre of gravity, the track is relieved from shocks, and the loco is made mechanically safe for speeds up to 85 m.p.h.

The case of a vehicle running on fixed rails is quite different from that of a motor-car on the high road. In the latter case the centre of gravity should be low, as overturning is the danger to be guarded against, and the height of the centre of gravity has no effect on liability to skidding. In the case of a railway locomotive a high centre of gravity is required, since there is no danger of overturning, as all curves are of known fixed radius and suitably banked, i.e. super-elevated. Furthermore a high centre of gravity lightens the wear on the track by enabling side-to-side motion of the vehicle to be cushioned by the springs, instead of allowing it to be thrown directly on the rails.

Some further details of these locomotives are given below in paragraph 918.

Three-Phase Locomotive.—As an example of an A.C. loco, those in use on the Italian railways may be given.* These have been designed for the mountain lines on which both freight and the international through expresses travel. There are grades of 2·6 and 2·7 % and up to 3·5 % on the Mont Cenis line. The total weight of the loco is 75 tons, distributed on five coupled axles, and two 3-phase induction motors of 1 400 H.P. are fed directly from the overhead line at 3 600 V, and 16½ cycles. By means of a triangular rod the motors drive the middle axle, and the others are coupled to this by ordinary connecting rods. The control gear enables the

* *El. Rev.*, Vol. 92, p. 525.

motors to operate with 8 or 12 poles as well as in cascade, giving four normal speeds of $9\frac{1}{2}$, $15\frac{1}{2}$, 19 and 31 m.p.h. A liquid resistance is used for starting. Auxiliaries are worked from two 12 kW, 100 V transformers—compressors, cooling fans, pumps for the automatic liquid rheostat, and a boiler for steam heating of the carriages. The efficiency of the motors is from 85 % upwards and the power factor between 75 and 85 % when on series connection and between 80 and 97 % in parallel. The tractive effort at 16 m.p.h. is 16 tons.

873. Self-contained Locomotives.—Of self-propelling cars and locomotives, independent, or partly so, of an external source of supply, there are three main types :—

- (i) Turbo-electric locos,
- (ii) Oil-electric locos,
- (iii) Battery locos.

There is a considerable, and very little explored, field for all of these on railways—whether steam or electric—with infrequent services, especially on either side of junctions and for inter-urban work. The hard-headed business men who run our railways are presumed to know more about their economic working than mere technical men and theorists ; but the fact remains that omnibuses and other road vehicles are filching all their short distance traffic while they look on with folded hands and say ‘Kismet’—or ask for Parliamentary powers to compete on the high roads. It is true that by far the greater part of their gross revenue comes from goods traffic ; but the nett revenue depends on all classes of traffic for exceeding the expenditure with a margin for dividends.

Let any reader pick up his ‘Bradshaw’ and take at random from the map two stations adjoining his nearest junction, but on different branches. The distance from one such place to another may be 5 or 10 miles and the time taken over it an hour or more by rail, of which a third is spent in changing and waiting at the junction. What wonder that the traveller takes a bus ?* It may be true that there is not much present traffic between two such villages close together, though the buses have developed some ; but

* *E.g.* Worplesden to Brookwood, via Woking, Southern Railway. Distance by rail, 6 miles ; by road, 8 miles. Time taken by rail, 1 hr. 50 mins. ; by bus (not taking the above shortest route), 21 mins.

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the case in the footnote has been cited as a *reductio ad absurdum*, and both train and bus cover the places beyond in both directions, where the contrast is only a little less marked and the traffic far more. Clearly self-contained vehicles could connect up adjoining branch lines without more than a minute or two stop at the junction; and quite certainly they could be fitted into the time-table. At most they might have to go into a siding for a minute to pass an express and yet be able to average something better than the 10 m.p.h. of the petrol bus or the antediluvian branch line steam engine. But even where these 'rail cars' are used, they are mostly steam-operated at present; as for example on the London & North-Eastern Railway, where such cars, with a capacity of 65 passengers and 26 strap-hangers, and a speed of 45 m.p.h. are being used in the Newcastle area.

A *turbo-electric locomotive* carries its own generating station, and thus gets the benefit of an electric drive without incurring capital expenditure on transmission lines or losses in transmission from an outside source. On the other hand, so small a central station cannot generate at nearly so low a cost as a large fixed one; and it would at first sight appear to be a thoroughly uneconomical arrangement to have a steam boiler and turbine with dynamo and motor in place of the engine and boiler only of a steam loco. But the advantages of perfect regulation, high acceleration and the elimination of reciprocating gear—despite the fact that this has been reintroduced in large electric locos—make the combination worthy of further trial.

An experimental 'Ramsay' condensing loco of this type was built by Armstrong, Whitworth & Co. in 1922 and has since been tested under working conditions by the London Midland & Scottish Railway.* Briefly the leading details are as follows:—

The loco is in two sections, connected by a universal joint; the front portion contains the forced-draught boiler, generating superheated steam (300° F.) at 200 lb. pressure, together with the main impulse turbine of nine stages and 36 in. mean blade diameter, with a speed of 3 600 r.p.m. This drives a 3-phase, 890 kW, 600 V alternator. An auxiliary single-stage turbine drives a D.C. generator for excitation and auxiliaries. The back portion of the loco carries the revolving-tube evaporative condenser [§ 175 (2)] aided by a fan. The condensate is returned to the boiler, the condensing water being carried in a separate tank. The coal bunkers are also carried on this portion. The four main driving motors are 600 V A.C. slip-ring ventilated type, each of 275 B.H.P. continuous rating and 360 B.H.P.

* *The Railway Engineer*, January, 1924, p. 5.

one-hour rating. The speed at 60 m.p.h. is 1 175 r.p.m. Each pair of motors is bolted to a centre stretcher carrying a transmitting shaft and spur wheels; pinions keyed to the motor shafts gear with the spur wheels, power being transmitted through coupling rods. The tractive efforts at the wheel rim for the accelerating period are—

	At starting,	22 000 lb.
	„ 15 m.p.h.	22 000 „
	„ 30	11 050 „
	„ 60	8 600 „
Normal running	60	6 000 „

At starting the main turbine is run up to half speed (1 800 r.p.m.) and the motors are switched in while connected in cascade; with this combination 3 times the normal torque is obtained. The overall length of the loco is 69 ft. 7½ ins.; drivers, 4 ft. diam.; weight, 154 tons; normal ratio of adhesion to tractive force, 12·05 to 1 (§ 890). This loco has been regularly running for some time with loads up to 275 tons and speeds up to 60 m.p.h.

The *oil-electric locomotive* has the same advantages and disadvantages as the turbo-loco, but substitutes the oil or petrol engine for the boiler and turbine. The improvement of the Diesel engine in recent years, in connection with submarines, has had its repercussions in this more peaceful direction. To the obvious advantage of absence of smoke, more economical operation may be added, the efficiency being about 25 % as against 15 % for the turbo-electric loco. A number of these, weighing from 60 to 100 tons, are in use in America, where it is anticipated that they will prove particularly useful on suburban work and in yards. Also there is scope for them—though not in this country—where clean feed water is unobtainable and boiler tube replacements are consequently frequent.

A 100-ton shunting loco of this type was successfully put into service on the Long Island Railway (U.S.A.) in 1926,* where it was employed to haul a 1 200 ton load. It has an overall length of 46 ft. and a wheel base of 36 ft., with a total weight on four driving axles of 200 000 lb. The equipment consists of a vertical, six-cylinder, four-cycle oil engine, with 10-in. pistons and 12-in. stroke, developing 300 H.P. at 600 r.p.m. and with a consumption of 0·43 lb. of oil per B.H.P.-hr. To the oil engine is direct coupled a six-pole, D.C., differential compound wound, commutating pole generator, together with a four-pole 60 V exciter. A 32 V storage battery is also supplied for excitation at low speeds. There are four D.C. series motors of the single-gear, box-frame G.E. 69 C railway type, each supported in its axle and bearings by the motor nose on the trunk transom, the gearing giving a maximum loco speed of 30 m.p.h. The differential winding ensures that the voltage is about inversely proportional to the tractive effort; the output and the voltage automatically adjusting themselves to meet the requirements of the service. The only operating handles are consequently the throttle lever controlling the engine output, and the series-parallel and reversing motor switches. A petrol-driven air compressor, with high-pressure air tanks for starting; a water heater for use when the engine is not running; and 2 400 sq. ft. of radiator for cooling the jacket water complete the outfit.

* *El. Rev.*, Vol. 99, p. 91.

Diesel-electric rail cars, made by Beardmore of Glasgow, are in use on the Canadian railways.* An eight-cylinder Diesel engine, rated at 320 B.H.P., of the light type developed for aeroplanes, drives a 200 kW, 600 V, D.C. generator, which in turn drives four 100 H.P., 600 V motors.† A storage battery is added for starting up and working accessories, and can take the car a short distance in case of breakdown. An average speed of 52 m.p.h. was attained on trial over 117 miles, with an oil consumption of one gallon for $3\frac{1}{2}$ miles. The car is articulated, with 4-wheel bogies at each end and one at the centre; its length is 102 ft.; weight, 94 tons; capacity, 126 passengers. Trains driven in the same manner are in use on the Buenos Aires Great Southern Railway; and the L.M. & S.R. is experimenting on the Manchester-Blackpool line with a similar Diesel-electric locomotive of 500 H.P., capable of drawing a 4-coach train at 50 m.p.h.

Diesel-electric cars are also in use on the Swiss Federal railways. An 8-cylinder, 4-cycle engine is used, developing 250 B.H.P. at 550 r.p.m. A 6-pole, 750 V, D.C. generator is direct coupled to the engine. A nickel-iron battery of 90 cells is also installed for starting, etc. There are two self-ventilated motors with a continuous rating of 56 kW and one-hour rating of 70 kW, used with series-parallel control, the gear ratio being $4\frac{1}{2}$ to 1. The empty coach weighs 57 tons and the fuel consumption on test was 0.024 lb. of oil per ton-mile. Assuming a calorific value of 18 000 B.Th.U. per lb. of oil, this consumption is equivalent to 4 500 B.Th.U. = 1.32 kWh (§ 52) per ton-mile.

The possibility of using Diesel-electric locomotives for main-line traffic in Great Britain has been discussed in the Weir Report and elsewhere, and a comparison between this and other methods has been made‡ from which the following figures are taken. On an average load factor of 50 per cent. for the complete electrification of the main lines of this country, the total power of the steam turbines, or other prime movers, required in electric power stations would amount to 3 450 000 B.H.P.; but if Diesel-electric traction

* *Daily Telegraph*, Oct. 14, 1925.

† These figures, as quoted, appear odd. But the Diesel engine rating is evidently on motor-car lines, and a smaller one rated at 160 B.H.P. gave 250 B.H.P. on test, so that this 320 H.P. engine would give 500 B.H.P. It is harder to explain the 200 kW generator serving 400 H.P. of motors.

‡ 'Primary Considerations Relating to Steam, Electric and Diesel-electric Traction,' H. W. H. Richards. *Inst. C.E.*, Paper No. 4908.

were adopted throughout, the total Diesel engine power would amount to approximately 15 000 000 B.H.P. On the same basis it is estimated that the total weight of electric tractors would amount to 845 000 tons, as compared with 1 307 000 tons for Diesel-electric tractors. The original paper should be referred to for further details.

High-Speed Diesel-Electric Motor Coach of the German Reichsbahn.—The 'Flying Hamburger' of the German Reichsbahn is a Diesel-electric vehicle accommodating 102 passengers, and scheduled to complete the 180-mile journey between Berlin and Hamburg at an average speed of 77 m.p.h., the maximum sustained speed on clear track being about 100 m.p.h. The coach is built in two parts, supported at each end by a bogie containing a 405 H.P. Diesel-electric D.C. generating set, and carried at the centre by a third bogie, the two axles of which are each driven through 1:2·62 gearing by an electric motor supplied by one of the Diesel-electric sets. For details of the coach reference may be made to the technical press.* The Diesels are Maybach 12-cylinder Vee-motors, rated at 405 H.P. (continuous), 1 400 r.p.m., and consuming 0·4 lb. oil per H.P.-hr. Either of the Diesel-generator-motor sets is alone capable of driving the coach at 75 to 80 m.p.h. if the other be disabled.

The Gebus system of control is used in the generator-motor circuit, this offering the advantage that the driver's duties are simplified. The essential feature of this system is the use of a generator of such characteristics that it automatically absorbs the full driving power available at any moment. With the exception of a main contactor, which opens the generator-motor circuit when emergency braking is applied, the only switchgear between the two machines is a reversing switch. The power developed is regulated by varying the speed of the Diesel engines. The generators do not excite at the 'light' speed of the Diesels (750 r.p.m.), but they are self-exciting at higher speeds. For each value of power output, as determined by the Diesel speed, the current and voltage in each generator-motor circuit adjust themselves automatically so that the output of the Diesels is exactly absorbed. The Diesels are started by running the generators temporarily as motors from a 96-V

* *Railway Gazette*, Vol. 57, p. 791; Vol. 58, p. 121. *Railway Engineer*, Vol. 54, p. 88. *Electrical Review*, Vol. 112, p. 775.

battery, the two halves of which, in conjunction with auxiliary generators, light the respective halves of the coach. The essential feature of the control is that the current-voltage curves of the generators correspond closely to the power curves of the Diesels over the working range of Diesel speeds (1 100 to 1 400 r.p.m.); at any given engine speed, the generator voltage increases (or decreases) as the current decreases (or increases), thus maintaining constant power. Energy dissipated in an adjusting resistance in the shunt-field circuit of the generator is used to heat water in the refreshment buffet. All the engine controls are actuated electrically, and cab signalling and train control apparatus is operated by track magnets (interlocked with the signals, points, etc.) should the driver attempt to overrun signals or exceed prescribed speed limits.

Battery locomotives are self-propelling but not self-contained in the full sense that the two previously mentioned types are, as their radius of action is limited by the capacity of the battery, which must be re-charged from an outside source. The main use of battery cars is for road and platform vehicles (Ch. 36), and they are also being employed to an increasing extent as locomotives in underground haulage (§ 832); in passenger work on rails their use is at present very restricted. For shuttle services and the like they are well adapted, and especially for shunting and yard work; and they would be a useful asset to central stations (in sufficient numbers) for off-peak charging. This latter consideration was often urged in vain in the past, when all traction systems had their own power-houses, and the levelling up of the load curve was a definite matter of £. s. d.; but now the burden of improving the load factor has been shifted on to the Central Board and its 'peak load stations,' except to the extent that the price charged for bulk supply will vary with the load factor of each bulk consumer.

The largest battery locomotive hitherto built is in service on the Chicago and North-Western Railway, and weighs 110 tons. It is capable of hauling a 1 500-ton train at 8 to 10 m.p.h. and a 3 000-ton train at shunting speed; it carries 40 tons of Exide ironclad batteries, *viz.* 120 cells of 2 700 Ah capacity at the 6 hr. rate of discharge.

The details of a typical battery locomotive,* built by the Midland Railway in 1913 to supersede horse-shunting in a London coal yard, are as follows: Weight, 17 tons 7 cwt.; draw-bar pull, 6 400 lb. maximum; normal load, 8 loaded wagons

* *Mechanical World*, July 29, 1921, p. 82.

(90 tons); maximum load, 12 wagons; speed, 7 miles per hour; unloaded speed, about 12 miles per hour; yard capacity, about 100 wagons; average weight per haul, about 30 tons; average length of haul, about 50 yds.; annual ton-miles, about 45 000 (excluding locomotive weight).

For information as to the distances traversed by battery vehicles on one charge see Chapter 36 (Road Vehicles). On rails, with lower track resistance, there will be a corresponding gain but no data are available.

Drumm Battery Coaches.—The Great Southern Railways of Ireland put into service, in 1930, an experimental coach weighing about 13 tons operated by Drumm storage batteries, which are of the zinc-alkaline type averaging about 1.9 V per cell (compared with about 1.2 V per cell for the iron-nickel-alkaline type, § 434, Vol. 2).

The following particulars concerning this battery are said * to be derived from the specification of patent No. 365,125/1932; patents applied for at later dates should be consulted as published. The specification cited states that: 'The invention consists in an alkaline storage battery in which the active negative material consists of zinc plated out of the electrolyte on to a supporting plate having a smooth, clean surface of nickel on monel metal . . . subjected to electrolytic treatment for the purpose of producing a hydrogen alloy at the surface. The electrolyte may consist of a solution of caustic potash of sp. gr. 1.22 to 1.25, at 15° C. Prior to the employment of this solution in a cell, however, it is made to dissolve zinc oxide to saturation, and when this solution has been filtered, it should have a specific gravity at 15° C. of between 1.245 and 1.275. Various forms of positive plate may be employed, and this may be of the tubular or of the flat-pocket form, but in each case the depolariser material consists of nickelic oxide or of silver oxide (as described in previous patent No. 335,587) or a mixture of the two. The nickelic oxide may be mixed with graphite or a mixture of graphite and silver oxide, or the conductivity may be improved by nickel thread or nickel gauze inserted in the active material. The negative plates or cathodes consist essentially of nickel gauze or monel metal gauze, the former being preferred on account of its greater electrical conductivity.'

It is suggested (*loc. cit.*) that, in view of difficulties encountered by previous inventors who have experimented with the zinc negative the following paragraph appears to contain the essential germ of the invention: 'The battery produced in accordance with the invention depends for its action on the fact that a nickel surface may be treated in such a way as to make readily possible satisfactory deposition of zinc metal from a concentrated solution of zinc oxide in caustic potash. To prepare the nickel surface of the gauze for satisfactory deposition of zinc it is necessary to treat the nickel surface to the cathodic evolution of hydrogen in ordinary caustic potash solution for several hours. During this time a change seems gradually to occur on the surface of the nickel whereby the over-voltage necessary for the discharge of hydrogen gradually rises to a value which is about that necessary for deposition of zinc in alkaline solution. No doubt the explanation of this phenomenon is associated with the surface formation on the nickel of a nickel hydrogen alloy. . . .

* *The Railway Engineer*, Vol. 53, p. 148.

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During the process of charging of the accumulator the zinc is plated out of the solution of caustic zincate on to the nickel negative in the form of a dense bright deposit which is completely free from spongy or loosely adhering zinc. . . . When discharging the accumulator to excess for long periods of time, the addition of aluminium hydrate or of beryllium hydrate, or both, is advantageous, and we find that such additions may be of the order of 1 % of the weight of the electrolyte for aluminium hydrate and 0.5 % for beryllium hydrate.'

It is stated that it is undesirable to allow the new accumulator ever to exceed 35° C. (95° F.).

Following the results obtained with the experimental coach, it was decided that battery coaches should replace steam-operated trains between Dublin and Bray, where intensified suburban service is worked on a line $14\frac{1}{2}$ miles in length, averaging 1.2 miles between stations. The coaches will operate up to 300 miles a day, and the batteries will be charged during halts at terminal stations, which average up to 15 mins. per hour. The following data are given (*loc. cit.*) concerning the new vehicles and their batteries :—

Battery voltage, 500 V (264 cells).

Dimensions of cell, $13\frac{1}{2} \times 10 \times 15$ ins. high.

Weight of cell, 130 lb.

Capacity of cell, 150 Ah at $\frac{1}{2}$ -hr. rate; 300 Ah at 1-hr. rate; 600 Ah at 2-hr. rate.

Maximum discharge current, 1 500 A for 30 secs.; 300 A for $\frac{1}{2}$ -hr.

The charging current is said to be 500 A for 20 mins. at start; 300 A for $1\frac{1}{2}$ hrs. at finish; maximum boost, 720 A. Time to charge, 1 min. per mile of run. Mileage per charge, 15 miles normal, 90 to 100 miles maximum. Ah-efficiency, 90 to 93 %; Wh-efficiency, 70 to 74 % (*cf.* § 484, Vol. 2).

The internal resistance of the new cell is stated to be about 0.25 to 0.2 times that of other alkaline cells of equivalent plate area. Regenerative braking has been facilitated and rendered more efficient by the ability of the Drumm battery to sustain rapid rates of energy input at regular intervals several hundred times a day.

The two-coach unit, with this battery equipment, is carried by a 4-wheeled bogie at each end and driven by two 200-H.P. motors, one on each axle of a central bogie which supports the adjoining ends of the two coaches. The two-coach unit seats 140 passengers and weighs 70 tons in running order (without passengers).

Two charging stations, at Dublin and Bray, are fed with high-voltage, 3-phase current from the Shannon power network, and provided with step-down transformers and rectifiers capable of supplying 900 A continuously at 630 V D.C. or 1 000 A for 30 mins., or 1 350 A for 2 mins.

At the time of writing, the authors are not aware of any specific data regarding the service performance of the Drumm battery coaches, but if expectations are realised these vehicles represent an important advance in battery traction.

874. Industrial Locomotives.—In the preceding paragraph mention was made of the suitability of the self-contained loco-

motive for such work as shunting; and the following abstract * presents the case for industrial locomotives very lucidly:—

It has long been recognised that the small steam locomotive, for industrial purposes or in shunting yards, is wasteful and inefficient, but in the majority of cases this has been regarded as a necessary evil.

In most works one source of waste is in the handling of material with steam locomotives. Consider the proportion of time spent in doing useful work to the total time during which the steam locomotive is burning fuel and using water. Before going into service, steam has to be raised, necessitating the attendance of a fireman; then bunkers have to be filled and water has to be taken on board. During service, when not usefully occupied, the consumption of fuel and water still goes on, and in the majority of works these stand-by losses must necessarily be considerable. After service the fires have to be drawn and the ashes cleared away.

In addition to this daily waste, the steam locomotive must be withdrawn from service at intervals for boiler washing, repairs to fire-box, repairs to glands and numerous other small fittings. At long periods the steam locomotive must have its boiler thoroughly cleaned and re-tubed. During the time these repairs and renewals are being effected, besides the labour and inconvenience entailed, the locomotive represents capital laid idle.

As an alternative, it is claimed that an electric locomotive eliminates a great deal of this waste. It is ready for use when required. There are no stand-by losses.† At the end of the day it can be put in the shed and left. The drive is through rotational machinery, and, consequently, the torque is even, which means that the driving parts do not have to withstand the impulsive forces to which the steam locomotive is subjected. Repairs are infrequent and quickly effected.

A steam locomotive must be engined for the heaviest load to be hauled, but this is not the case with an electric locomotive. The latter can be motored for the normal load, as it is capable of sustaining heavy overloads for short periods.

In addition to the above points, the electric locomotive scores because it is clean, needs the minimum amount of labour for driving, and is less likely to cause fires. There is always danger of fire with a steam locomotive, due to sparks and red-hot cinders, and it is a fact that insurance companies are willing to accept smaller premiums when electric locomotives are substituted for steam locomotives.

The works in which locomotives are used may be divided broadly into two kinds:—

- (1) Those which require intermittent service.
- (2) Those which require continuous service.

In the first class there are power stations, gas works, and small factories where the large railways deliver and collect material three or four times a day.

In the second class there are colliery yards, steel works, and large works generally.

In addition to these, there are others where special conditions exist, such as wood yards, docks, paper mills, etc., where cleanliness and the prevention of fire are of great importance.

* *Electricity*, Aug. 19, 1921; reprinted from the *English Electric Journal*.

† There are, of course, stand-by losses in the central station supplying the power, if the locomotive is not self-contained; but these are small in comparison.

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For the first class a battery locomotive may be used, while, generally speaking, a trolley locomotive is recommended for the second class. There may, however, be objections to the installation of overhead wires, and then the battery locomotive must be used.

Sometimes a combination of the two is advisable, as in the case of the ordinary steel works. A steel works usually has a fairly level track alongside the furnaces and a heavy grade up to a slag tip; near the furnaces, overhead wires are objectionable, but up the grade they can be installed without inconvenience. On the level, therefore, it is necessary to use a battery, but up the grade, where a heavy demand would be made on the battery, the locomotive runs on the trolley wire. The use of the trolley wire up the grade enables the battery to be kept within reasonable dimensions, or alternatively, it does not need to be charged at such frequent intervals.

As a guide to the relative costs of steam and electric locomotives on a basis of work done, the following figures have been compiled, and although it is not claimed that they will apply in all cases, there is no doubt that they are representative and do not unduly favour the electric locomotive. The figures for repairs and maintenance, depreciation and interest on capital include all charges attendant on each system. For steam locomotives account has been taken of coaling, watering and repair plant, and for electric locomotives, overhead line, battery charging, converting and repair plant have been allowed for.

In the following table 100 has been taken as a basis figure for each item:—

	Steam.	Trolley.	Battery.
Repairs and maintenance	100	33	50
Power	100	33	40
Lubrication and miscellaneous	100	33	53
Wages	100	50	50
Depreciation	100	60	90
Interest on capital	80	100	100

The overall operating costs of the three systems are in the following proportion:—

Steam 100, Electric Battery 60, Electric Trolley 50.

The only item in which steam traction compares favourably with electric traction is in capital cost, but the total annual saving in operating costs is such that even with a small system this extra cost is wiped out in less than two years.

The figures given above are for small systems where only one locomotive is used. On larger systems, however, greater economy would be effected by the use of electric traction, as a number of steam locomotives can be displaced by a smaller number of electric locomotives. The proportion varies according to the nature of the service. For intermittent service two electric locomotives would do the same amount of work as three or four steam locomotives. Where the service is continuous, one electric locomotive of the trolley type would be required in place of each two steam locomotives, while, if battery locomotives were employed, one such and one spare battery would be necessary.

The larger the system the greater becomes the ratio of steam to electric locomotives required for the work, and this difference offsets the higher cost of the electric locomotive. In further consideration of the capital cost, it is important to remember that where, with steam work, a spare locomotive would be required, an electric system requires only a spare armature. Also, electricity is so generally used for power purposes that the majority of works would only incur a small additional cost by installing the necessary plant for supplying current to the line or charging

batteries. In regard to this auxiliary plant, it is well to point out that an increased number of locomotives requires only a small increase, if any, in the overhead and battery charging plant provided. The overall capital cost per electric locomotive is thus reduced where several locomotives are employed, and the total capital cost is little different from that of the requisite number of steam locomotives with their water, coal and repair plant.

Many locomotives suitable for such industrial service have been both designed and constructed for gauges from 18 ins. up to 5 ft. 6 ins., and of weight from 4 up to 22 tons, some with trolley equipment, others with batteries, and yet others again with both systems combined. Standard interpole traction motors are used, geared down for the low speeds mostly required in this class of work.

PROJECTS AND SERVICE.

875. Data Required for Project Estimates.—In order to lay out the general lines of an electric tramway or railway project, for the preparation of a preliminary estimate, we must first ascertain—

- (a) The length of the route to be traversed; the proposed gauge; the gradients, and length of each; the curves on the route; the volume of passenger and goods traffic to be carried at different times and seasons; and the frequency and speed of the service required to cater for the particular traffic to be dealt with.

From these 'field data' the next step is to determine—

- (b) The number of tracks and the number and capacity of the cars required, whether tramway cars, rail motor-cars, or passenger or goods rolling-stock drawn by locomotives. Also the maximum permissible weight per axle; size of wheels; load and structure gauge; speed limits.
- (c) The system to be used.

It will then be possible to work out, on the lines of the following paragraphs,

- (d) The maximum and average power required by each car, in order that the number, horse-power, and rating of the motors may be determined; or, if locomotives are to be used, the same particulars for these;
- (e) The maximum power required for the whole project and also for each section of it, so that the size of the plant and the feeders may be worked out; and also the average

power, on which the total consumption of energy in units depends.

We may assume that the length of road to be served is known. With a sufficient density of traffic double track is of course preferable; with a single-track tramway, turn-outs must be arranged at intervals for crossing, and in the case of a single-line railway the stations will serve this purpose. The gradient on the line, and particularly the maximum ruling or 'virtual' gradient,* is a most important condition of the problem.

876. Rolling Stock and Service (Tramways).—In the case of a tramway, single motor-cars are preferable to motor and trailer cars, though the latter are often used where there is sufficient density of traffic or where two classes of accommodation are required. The number of cars required in service upon any particular route

$$= \frac{60 \times \text{length in miles of round trip or double journey}}{\text{minutes apart of cars} \times \text{average speed m.p.h.}}$$

On Indian tramways the average speed is at present very low, about 6 or 7 m.p.h., owing to the length and frequency of the stops; in England it is over 8 m.p.h.; American 'inter-urban' lines, similar in style and equipment, run at high speed and may average over 20 m.p.h., having far fewer stops. The service, or number of minutes apart of the cars, will vary according to the time of day and volume of traffic from about 10 or 15 mins. on outlying sections to 1 min. or less in the busiest time of day and at the central parts of the system, where cars from a number of routes converge on to the same track.† In working out the number of cars, each route or section must be taken separately, even though part of it may be traversed by cars from other sections.

877. Rolling Stock and Service (Railways).—In the case of railways, where higher speed and carrying capacity are needed, either an electric locomotive and train of cars may be used or a number of motor-cars may be coupled together and multiple-controlled from the front car; the latter method is preferably used where the gradients are very severe in order to obtain sufficient

* *I.e.* omitting such short steeper lengths as will be negotiated by the momentum of the car or train.

† The greater the headway, the less is the return on the capital spent on the track; and the more surely does the motor-bus—paying no rates or track rent—oust the train.

adhesion (§ 890) and also in rapid-transit suburban work, where this is required on account of the high acceleration used. Although in both steam and electric practice a train is often run up short gradients by momentum (*cf.* motor-cars), in cases where the loco cannot even maintain the speed of least resistance, there is always the possibility of the power supply being cut off an electric line; and the car or train must in such cases be capable of starting again from rest on the ruling grade. Mountain railways combine both severe gradients and sharp curves, and in extreme cases a locomotive working on a rack is necessarily used. Generally speaking, locomotives are more suitable for long distance running, and multiple-unit trains for suburban lines with high acceleration and frequent stops; for in the latter case again there would be slipping at the moment of starting, with destructive results to driving wheels and track, if the adhesion were insufficient for the very rapid start from rest—or, rather, the acceleration would be limited severely. Urban and suburban rapid transit lines also differ from main lines in having no slow goods traffic, and in being able to work on a perfectly even schedule, which is an essential of such service.

On railways, where the speed must necessarily vary a great deal, and the stations are at varying distances apart, the locomotives or motor-cars required must be determined with reference to the time-table to which it is proposed to work on the busiest day, or, in the case of a short line, during the busiest hours of the busiest day.

Into the question of time-tables, covering both passenger and goods trains—the latter by far the most important from the revenue point of view—this volume cannot enter; but it is clear that when main lines are electrified both slow goods and fast passenger traffic must adopt the system. Half steam and half electric working is only tolerable during the transition stage, when smoke and cinders do their worst on the equipment.

POWER AND ENERGY CALCULATIONS.

878. General Considerations.—The fundamental principles applicable to calculations of the power required to propel a vehicle, and the total amount of energy used by one or by a system of vehicles, are the same whether we are considering a tramway, an express or a suburban railway, a road vehicle or a mining haulage, all of which are treated in this and the succeeding chapters. The

matter may be treated either from the general point of view of elementary mechanics or from the specific outlook of the traction engineer, and both methods are here dealt with *seriatim*, as it is believed that both may be useful according to circumstances. The second method, it will be seen (§ 886), assumes that the approximate H.P. of the motors is known in advance, and that their characteristic curves are available.

First, these elementary mechanical principles are laid down (§§ 880 to 885), illustrated step by step, according to our practice in these volumes, by simple progressive examples; beginning with level track and uniform speed, continuing with gradients and accelerations, and summing up with a general expression applicable to all circumstances. We have taken a single tramcar as the most convenient unit for illustrative purposes in each paragraph, showing in detail the disposal of the power taken from the line to operate it; later, (§ 888) the special supplementary considerations applicable to railway traffic are explained and similarly illustrated.

Next (§ 889) the specifically electrical method of speed-time curves is explained, again, with an example based on a single tramcar.

Following on the above, the estimation of energy consumption on individual vehicles and systems is dealt with (§§ 888 and 889), first as regards railways, and then as to tramways, with examples as before. Although in most cases in this country power will in future be taken from the public network, the consideration of power plants designed *ad hoc* cannot yet be ignored here, and still less abroad. Various matters interwoven with the consideration of power and energy are brought together in the following section, under the heading of 'Practical Considerations and Data'.

879. Disposal of Power Applied to a Vehicle.—Apart from the power lost in the speed reduction gearing and the motor itself, the mechanical power delivered by the motor to the wheels of the car or locomotive is used:—

- (i) To overcome the resistance of the track, journal friction, and air resistance (§ 891).

This varies with the force and direction of the wind, the nature and state of the track, the speed and shape of the stock, and whether in a tunnel or not; the tractive coefficient may be expressed either as a percentage of the total weight of the loaded

car or (more usually) in lb. per ton, as herein. The value may be as low as 3 lb. per ton in the case of railway vehicles, at the speed of least resistance,* and without wind, rising to about 21 lb. per ton at 50 m.p.h. It will vary from 12 lb. up to 20 or 30 lb. on straight lengths of grooved rail tramway track; in mining haulages, with straight track, a resistance of 67 lb. per ton has been measured. The starting resistance is much higher, especially when the stop, as in the case of a breakdown, is of considerable duration and the lubricated parts have had time to cool down. On curves the resistance may be increased to double the above figures; in railway practice curve resistance is considered independently of track resistance, but in tramway work this is hardly practicable. On 5 ft. 6 in. gauge railways it amounts to about 0.04 % of the weight per degree of curvature.† It is usual to take 30 lb. per ton as a fair average value for resistance on tramways, as in the examples that follow; but see § 891.

(ii) To climb gradients (§ 881).

(iii) To increase the speed of the car (§ 882).

On downward slopes and with decreasing speed the last two items represent negative power, and in some systems this is returned to the line (§ 900); ordinarily it is absorbed in brake friction.

In every case the applied H.P. = ft.-lb. per min. / 33 000 = resistance overcome \times velocity in ft. per sec. / 550; so that, given the speed, it is required to find the equivalent resistance in lb. The symbols used are as follows:—

W = Weight of loaded car in tons; but see § 882.

V = Speed in m.p.h. = $0.682 v$.‡

S = Gradient, per cent.

a = Acceleration (+ or -) in ft. per sec. per second.

k = Tractive coefficient expressed in lb. per ton weight of loaded car.§

* This is very low; of the order of 5 m.p.h.

† I.e. the number of degrees of central angle subtended by a chord of 100 ft. The radius of a curve of one degree is then 5 730 ft. and $D^\circ = 5\,730 / R$, where R is the radius in feet. Curves are generally expressed in feet radius to centre of track.

‡ The speed in feet per second, v , is $1.467 V$ and, reciprocally, $V = 0.682 \times$ feet per second.

§ Sometimes the tractive coefficient μ is expressed as a percentage of the weight of the loaded vehicle. Then $\mu = 0.044\,7 k$ and $k = \mu \times 2\,240 / 100$ or 22.4μ .

E = Combined efficiency, expressed as a decimal, *i.e.* efficiency per cent. / 100 of motors and gearing, taking into account losses in regulating resistances. For tramcars with single reduction gear E may be taken as about 0.75 (equivalent to 75 %).

880. Power Required for Uniform Speed on Level.—On a level track, at uniform speed, the tractive force required in lb., P , will be the product of the weight of the car and the tractive coefficient, *i.e.* $P = kW$. Then the H.P. *at the car wheel rim* to drive a car at V miles per hour on the level will be—

$$\text{H.P.} = 2\,240 \times (k / 2\,240) \times W \times (V \times 5\,280 / 60) \div 33\,000 \\ = 0.002\,67\,kWV.$$

Thus if μ be taken as 1.34 %, giving $k = 30$ lb. per ton, a car weighing 8 tons, travelling at 8 m.p.h. on the level, will require $0.002\,67 \times 30 \times 8 \times 8 = 5.1$ H.P. at the periphery of the wheel.

If the efficiency E is 0.75, the power delivered *from the line* to the car will be $5.1 / 0.75$ or 6.8 E.H.P. = 5.1 kW. [It will be noticed that as 0.75 kW is practically equivalent to 1 H.P., the result in kW from the line is also the B.H.P. of the motor on the assumed efficiency of 75 %.]

Looking at the matter from a slightly different point of view, the H.P. = $2\pi TR / 33\,000$, where T is the torque in pounds-feet on the wheel rim and R = wheel r.p.m. If the car in this example has 30-in. wheels, R = ft. per min. / circumference of wheel = $8 \times 5\,280 \times 12 / 60 \times 30 \times 3.14 = 89.5$ r.p.m.

Assuming it has a single motor only, we have

$$5.1 = 2 \times 3.14 \times T \times 89.5 / 33\,000 \quad \text{and} \quad T = 300 \text{ lb.-ft.}$$

The radius of a 30-in. wheel is 1.25 ft., so the pull must be $300 / 1.25$ or 240 lb.

881. Power Required on a Gradient.—If the gradient is S %, the *extra* H.P. required solely to lift a car of given weight up that gradient at V m.p.h. is

$$\text{H.P.} = W \times 2\,240 \times (S / 100) \times (V \times 5\,280 / 60) \div 33\,000 = 0.06\,SWV.$$

Thus if the car in the previous example is travelling at a uniform speed of 8 m.p.h. up a gradient of 5 % or 1 in 20, the *additional* power required at the car wheels to overcome the gradient will be $0.06 \times 5 \times 8 \times 8 = 19.2$ H.P. This is equivalent to

$19.2 / 0.75 = 25.6$ E.H.P. or 19.1 kW extra delivered to the car; making the total 32.4 E.H.P. or 24.2 kW.

Combining the expression for level running with that for a gradient, the power required at the wheel rims for ascending a gradient at uniform speed becomes

$$\text{H.P.} = 0.06 WV (0.0447 k + S),$$

so that in our example we have $\text{H.P.} = 0.06 \times 8 \times 8 (1.34 + 5) = 24.2$ as before.

Taking into account the efficiency, E , and the fact that the gradient may be downward, the power taken from the line at uniform speed

$$\text{E.H.P.} = 0.06 WV (0.0447 k \pm S) \div E.$$

On a similar *falling* gradient at the same speed, the car will require no power other than gravity; it will in fact develop at the wheel rim, the difference between the 19.2 H.P. for the negative gradient and 5.1 H.P. for overcoming the resistance of the track, i.e. 14.1 H.P., which will be disposed of in braking, regenerative braking (§ 900), or in speeding up the train.

882. Power Required for Acceleration.—The difference between the final and initial speed divided by the time gives the mean acceleration; thus, if a car attains a speed of 10 m.p.h. (14.7 ft. per sec.) from rest in 10 secs.,* the mean acceleration is 1 m.p.h. per sec. or 1.47 ft. per sec. per sec.—abbreviated into 1.47 ft. per sec.²; 8 m.p.h. in $\frac{1}{2}$ min. = 0.39 ft. per sec.², and so forth. Just as under the acceleration of gravity the distance travelled, when starting from rest, is $\frac{1}{2}gt^2$, so under any other uniform acceleration, a , the distance travelled = $\frac{1}{2}at^2$. The tractive effort which will increase the speed of a car at the rate of a ft. per sec.² is the same as that which will overcome a gradient of $3.1 a \%$ or 1 in $(32 / a)$. Thus at 1 ft. per sec.² the tractive effort (neglecting friction) must be $(W \times 2240 \times 3.1 \times 1 / 100) = 69.5$ lb. per ton, and at 1 m.p.h. per sec. 102.1 lb. Therefore the *extra* H.P. on the wheel rims required for acceleration (or absorbed in retardation) is

$$\text{H.P.} = 0.06 WV \times 3.1 a \quad \text{or} \quad 0.186 a WV.$$

Taking into account the losses, as before, this becomes

$$(0.186 a WV / E),$$

* The average acceleration on electric trains (multiple unit) is about 1.2 m.p.h. per sec. as against 0.5 m.p.h. per sec. for steam.

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where E is a decimal, and in this form it is added into the general expression given below for the power delivered to a car. In calculations of acceleration and deceleration an allowance has to be made for the fact that a considerable amount of energy is required for speeding up rotating masses, *viz.* wheels and motor armatures. This inertia of rotating parts is dealt with in practice by an addition to the weight of the car or train, varying from 6 % for a heavy freight train to 12 % for a rapid transit line. For tramways the allowance is usually taken as 10 %, and in our examples this must be borne in mind.

In any moving car a certain amount of energy, or capacity for doing work, is stored up, depending on the mass of the car and the velocity it has attained at the moment. The stored energy in ft.-lb. = $\frac{1}{2}mv^2$, where m is the mass (or weight in lb. divided by g), and v is the velocity in ft. per sec.; this may be expressed as

$$W \times 2\,240 \times v^2 / 2 \times 32.2 = 34.8 W \times v^2 \text{ or } 74.8 W \times V^2.$$

To maintain constant acceleration from rest to velocity v during a given time, work must be done at an average rate of $(\frac{1}{2}mv^2 / t)$ ft.-lb. per sec. or $(74.8 W \times V^2 / t)$, where t is the given time in seconds; the result divided by 550 gives the *average* H.P. exerted. If the acceleration is uniform the actual H.P. exerted from time to time increases with the speed.* Thus, as in the previous examples,

W : 8 tons (effective) †; then $m = 8 \times 2\,240 / 32.2 = 556$.

V : 8 m.p.h.

v : 11.7 ft. per sec.; $v^2 = 138$.

t : time required to reach the above speed from rest, say 30 secs.

Then $a = (8 - 0) / 30 = 0.266$ m.p.h. per sec., if acceleration is uniform, or $(11.7 - 0) / 30 = 0.39$ ft. per sec.² Then, by the first formula given (line 15 of this paragraph), the *maximum extra power* required for acceleration alone is

$$0.186 a W V = 0.186 \times 0.39 \times 8 \times 8 = 4.64 \text{ H.P.}$$

* In practice, however, the acceleration is not uniform; it decreases as the time approaches for notching up on the controller. And for simplicity we have assumed E also to be constant, whereas it is evidently nil at the moment of starting.

† For simplicity, W has been kept as 8 tons throughout these examples, though more correctly it should here be $W_1 = W + 10\%$ as in a later example.

The *average power input to the train* required for effecting this acceleration is

$$74.8 W \times V^2 / 550 \times t = 74.8 \times 8 \times 64 / 550 \times 30 = 2.32 \text{ H.P.}$$

If the $\frac{1}{2}$ min. is divided up into three periods of 10 secs. each, with constant acceleration, the speed at the end of 10 secs. will be 3.9 ft. per sec. The distance travelled will be $\frac{1}{2} at^2 = 0.39 \times 100 / 2$ or 19.5 ft. At the end of 20 secs. the speed will be 7.8 ft. per sec. and the distance travelled 78 ft.; at the end of the third second the speed will be 11.7 ft. per sec. and the distance 175 ft. Then, (using v instead of V) and employing the first rule in the form $\text{H.P.} = 0.127 a W v$, we have

0—10 secs. Maximum H.P. = $0.127 \times 0.39 \times 8 \times 3.9 = 1.54$,
having risen from nil at the beginning of the period.

10—20 secs. Maximum H.P. = $0.127 \times 0.39 \times 8 \times 7.8 = 3.09$,
from 1.54 H.P.

20—30 secs. Maximum H.P. = $0.127 \times 0.39 \times 8 \times 11.7 = 4.64$,
from 3.09 H.P.

Then average H.P. in first 10 secs. is $\frac{1}{2} \times 1.54 = 0.77$

“ “ “ “ second 10 “ “ $\frac{1}{2}(1.54 + 3.09) = 2.31$

“ “ “ “ third 10 “ “ $\frac{1}{2}(3.09 + 4.64) = 3.86$

This gives a mean value, as before, of 2.32 H.P.

Actually the mechanical power *exerted* by the motor rises steadily from the start, when the efficiency is nil, up to the maximum; whereas the power *from the line* is at the maximum as each fresh notch on the controller is actuated, and drops from that point until the time comes to notch up again.

883. Power Station Output Required in Acceleration.—In the foregoing paragraph, acceleration has been treated from the point of view of the mechanical power required at the wheel rims. It is now necessary to consider the special points which arise when energy is applied to accelerate a train from rest.

Power—in the engineering sense—measures the rate at which a force moves a body in the direction of its line of action; where there is no motion, there is no power. Hence the power associated with accelerating a train is, at the moment of starting, nil. This is shown by the formula of the previous section for the case of $V = 0$. This is the *mechanical power required at the wheel*

rims, and, if the tractive coefficient k is approximately constant, it increases (for a given acceleration) with the speed. This is also illustrated in the graphs of Fig. 396 below.

The output required from the power station is, however, an entirely different matter. At the moment of starting, and during acceleration until a 'running speed' is reached, the motors are required to give their maximum torque. For this, they require maximum current—*cf.* the ordinary series D.C. motor, where the torque is entirely a function of the current. But since the line voltage is fixed, this involves taking maximum power from the line, although (as pointed out above) the mechanical power required at the wheels is zero at starting and proportionately small at low speeds. It is necessary, in fact, to draw full power from the line in order to get maximum torque, and then to dissipate nearly all of this power

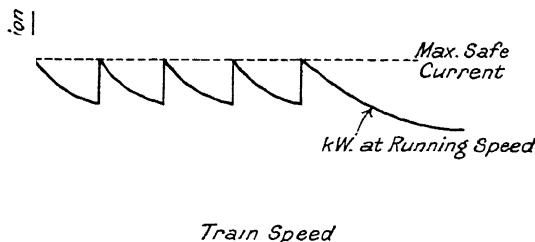


Fig. 396.—Energy demand during acceleration.

(all at the moment of starting) in resistances, it being impossible to use it. It is not possible to get torque from the line without power, or to use power in the motors without speed. Another way of looking at the matter is that the efficiency of the locomotive (including resistances) drops to zero at starting—a remark applicable to all machinery—and gradually improves as the dissipating resistances can be cut out with increasing speed.

Neglecting accidental variations of line voltage, the motor current is an index of the kW demand on the power station. During acceleration the current is kept closely up to the maximum safe value, to give the maximum torque. The actual curve of kW demand at the power station, for one train, is on the lines of that shown in Fig. 396, the sudden increases being where sections of resistance are cut out on the train. It will be seen that the power called for from the station is roughly at a constant maximum value until a running speed has been obtained, when it gradually

falls off. This is very different from the mechanical power at the wheels discussed earlier.

In the purely illustrative examples worked in this chapter, simplicity has been maintained by taking a constant line-to-wheel efficiency and a constant train resistance. The second of these simplifications is in the nature of a useful practical approximation for most purposes, but the first definitely makes the calculations inapplicable to a consideration of the demand on the power-house during the earlier stages of acceleration. A further point to note is that accelerations have been taken as constant. This will, on the average, and neglecting the current peaks, be true during the starting period, provided the train resistance is fairly constant, but when a running speed has been attained the acceleration gradually falls to zero as the speed rises and the motor current drops.

884. General Expression for Power Required.—Combining the equations given above, and taking into account both up and down gradients and positive or negative acceleration, the E.H.P. taken from the line is

$$\text{E.H.P.} = 0.06 \, WV (0.0447 \, k \pm S \pm 3.1 \, a) \div E.$$

Expressed in kilowatts this becomes

$$\text{kW from line} = 0.0445 \, WV (0.0447 \, k \pm S \pm 3.1 \, a) \div E.$$

Thus, if the acceleration is taken as 0.39 ft. per sec.², as in the preceding paragraph, a tramway car weighing 8 tons (effective) and travelling at 8 m.p.h. (as in the previous examples (§§ 880 and 881) on the level) will take from the line :

$$\text{kW} = 0.0445 \times 8 \times 8 [(0.0447 \times 30) \pm 0 \pm (3.1 \times 0.39)] / 0.75 = 9.7 \text{ kW, viz. } 5.1 \text{ for level running and } 4.6 \text{ for acceleration.}$$

On a 5% up-grade the power will be 28.8 kW, made up of 5.1 for level running, 19.1 for negotiating the gradient and 4.6 for acceleration. Should a number of cars be started from rest at the same instant, as may sometimes happen after a temporary breakdown, the momentary total demand on the line and the plant may be greatly in excess of the average demand; but of course the total resistance in circuit, coupled with the drop in line pressure in these circumstances, sets a definite limit in every case.

885. Outline of Practical Electrical Methods.—The above simple methods of working out the problem from first principles may now conveniently be supplemented by the second and more

practical way mentioned at the beginning of this section. decided on the particulars of the rolling stock and service required, the rating of the motors and the demand on the generating plant can be calculated. In practice most of this work is done empirically, using data based on previous experience for similar cases. Thus in D.C. suburban railway work, the size of the motors is roughly fixed by the fact that the approximately constant current per motor during rheostatic acceleration is usually about equal to the one-hour rated current of the motor. In further detail, the manufacturer can often select one amongst his existing designs which will, perhaps with modifications, give the required characteristics, and which on a basis of previous experience can be expected not to exceed the maximum specified temperature rises in actual service. In other cases previous work on existing designs is useful in the design of any new type, and provides the necessary information on which to base estimates of performance and heat dissipation.

When the motor characteristics have been worked out, calculation of generating and converting plant becomes mainly a matter of arithmetic; the line current taken by all vehicles or trains on any section of the system can be found from the train time-tables and the current-speed curves (§ 886) and can be totalled up to give the power demanded at the moment from the substations or the power-house, as the case may be. In practice this work is carried out by means of graphical time-tables. In estimating the peak demands, a suitable margin must be allowed for the possibility of trains not running to time, and in all calculations affecting the generating station and substations, allowances must be made for the various energy losses occurring in the plant and distributing system.

If estimates of energy consumption are required without reference to the detailed design of the motors, a figure giving the consumption in Wh per ton-mile can be based on actual results for work of a similar nature, where available. Some practical figures in this connection are given further on (§ 887).

886. Speed-Time Curve Method of Calculation.—Turn now to the alternative electrical method of dealing with these traction problems, as distinct from the mechanical. As a simple illustration of the principles involved, some calculations for a single D.C. tramcar on a single run may be given. These principles apply

equally to working out the requirements of a railway train, but the assumed data—especially in the matter of tractive resistance (§ 891)—will then be different. Let the car considered weigh 12 tons (actual, not equivalent, § 882), and the run be taken as 900 ft. between stops, with acceleration and braking rates of 1.6 and 1.5 m.p.h. per second respectively. A constant tractive resistance (§ 891) of 30 lbs. per ton is again assumed, this being a good average figure for tramway work, where the uncertain condition of the track and the low speeds justify such an approximation. The car is provided with a pair of 40 H.P. motors whose characteristics are shown in Fig. 397 (a). Fig. 397 (b) shows these same curves

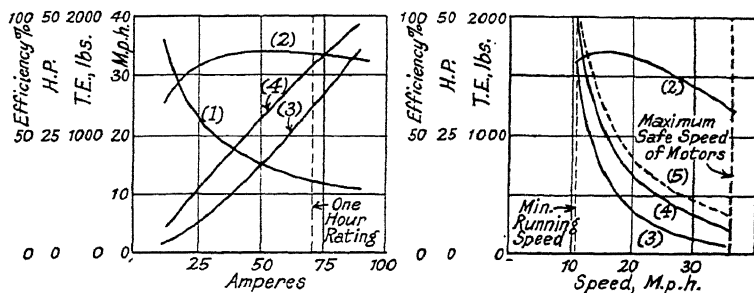


FIG. 397.—(a) Characteristic curves of 40 H.P., D.C. tramway motor.

(1) Speed, m.p.h.

(2) Efficiency % including gear

(3) Tractive effort of car wheels, lb.

(4) Horse-power output.

(b) The same, plotted to speed base.

(1) Efficiency % as before.

(2) Tractive effort.

(3) Horse-power output.

(4) E.H.P. input.

replotted and has been added to emphasise the manner in which the power and torque of a series motor vary with speed.

The calculation of the speed-time curve is carried out step by step in tabular form, as shown in Table 189. Over the constant acceleration period, and during coasting and braking, the problem presents no difficulty. Thus in the case considered, the time taken to accelerate to 12 m.p.h. is $12 / 1.6 = 7.5$ secs., and the distance travelled during this time is $\frac{1}{2} \times 1.6 \times 7.5^2 \times 88 / 60 = 66$ ft. Thereafter the speed range is divided up into appropriate small intervals, and the time taken to accelerate over each is worked out. The method is to read off from the motor curves the T.E. per motor at the mean speed of the range, find from this the total T.E. for all

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the motors concerned, subtract the total tractive and grade resistances in order to obtain the net T.E. available for acceleration, and thence work out the acceleration itself. This latter calculation can be made by means of the formula

$$\text{Acceleration (m.p.h. per sec.)} = \frac{\text{Net T.E. (lb.)}}{(102 \times \text{gross weight in tons})}$$

This statement simply expresses the second law of motion in practical units. Bearing in mind the addition to actual weight to allow for inertia of rotating parts (*supra*), the gross weight here is $12 + 10\%$ or 13.2 tons, and the formula for this particular case reduces to

$$\text{Acceleration} = \text{Net T.E.} / 1350.$$

TABLE 189.—*Calculation of Speed-Time Curves.*

(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)
Speed Bar	Mean Spe	E. per Motor.	$Gh \times 2$ (ft)	Net T.E. Col. 4 - 30	Acceleration Col. 6 / 1350	Time 2 / c	Total Time.	$\frac{\text{Area}}{\text{Col. 6} \times 2}$	
12-14	13	1 020	2 040	1 680	1.24	1.62	1.62	31	31
14-16	15	710	1 420	1 060	0.786	2.55	4.17	56	87
16-18	17	530	1 060	700	0.520	3.85	8.02	96	183
18-20	19	420	840	480	0.355	5.64	13.66	158	341
20-22	21	320	640	280	0.207	9.67	23.33	298	639
22-24	23	260	520	160	0.118	17.00	40.33	575	1214

The method of making the remaining calculations will be obvious from the notes under the numbered column headings. The resulting speed-time curve under power is shown in curve 1 of Fig. 398. The distance covered in any time is found by taking the area under the curve between the desired limits of time and converting it to feet by means of a factor depending on the scales used. For instance, the original of curve 1 on Fig. 398 was plotted to scales of $1/10$ in. = 1 sec. and $1/10$ in. = 2 m.p.h., so that each small square of $1/10$ in. side represented 2 m.p.h. for 1 sec. or $1 \times 2 \times 88 / 60 = 2.94$ ft.

Suppose now the run of 900 ft. between stops is to be made, one possible way of accomplishing this would be to run up under

power to a speed of just below 22 m.p.h., this process taking 29.5 secs., and then immediately to apply the brakes, it being assumed that all braking is carried out at 1.5 m.p.h. per sec. as already specified. The speed and energy curves of the run carried out in this manner are shown on the graph, and it is clearly very uneconomical from the energy point of view. It is, however, ruled out in any case by the fact that it provides no possibility of making up time, for which purpose a certain amount of coasting has to be included.

Curve 2 of Fig. 398 shows a second method of carrying out the run to meet practical requirements. The minimum time in which the distance could be covered with the existing equipment (curve 1) is 44 secs.; in order to provide a margin, this time has been

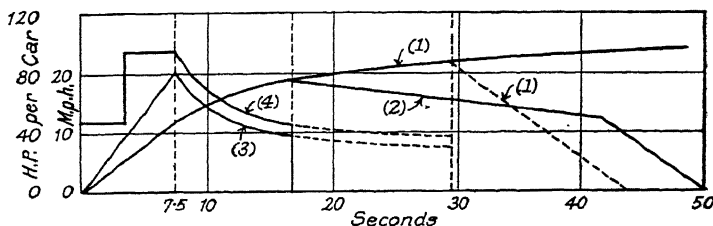


FIG. 398.—Speed-time curve of traction motor.

- (1) Speed-time curve for minimum time.
- (2) Actual speed-time curve.
- (3) H.P. output.
- (4) E.H.P. input.

extended to occupy 50 secs. by the introduction of a coasting period. The area under this curve 2 is naturally the same as that under curve 1, representing the 900 ft. travelled. In selecting the moment to begin coasting, in order to complete the run in any given time, trial and error must be used.

The energy output from the motors during the later part of the run can now be filled in from the motor characteristic curves and doubling, since there are two motors per car. The input over the 'running range,' after the resistances have been cut out, is similarly obtained, but over the period of acceleration on the rheostats the motor input bears no direct relation to the output and the conditions are special. In order to make the best use of the available motor power, the current per motor during this period is controlled to a constant value, resulting in constant tractive effort from the

motors * and therefore constant acceleration. Since the T.E. is constant it follows that the H.P. output varies uniformly from zero, at starting, up to its full parallel value. On the other hand, since the current is constant and is drawn from a (nominally) constant voltage line, it follows that the power input to the motors is constant. This involves considerable waste of power, which is inherent in the method of control, since full power is of necessity drawn from the line the whole time merely in order to provide torque in the motors, this torque representing, when the speed is low, a correspondingly small power return on the output side. The balance of the energy input which cannot be used by the motors has to be dissipated in the rheostats. Some of this waste is saved by series-parallel control, which halves the line current while retaining the same current per motor during the first half of the starting period. The current or power input during the rheostatic acceleration period with series-parallel control can therefore be approximately represented by the stepped straight line in curve 4 of Fig. 398.

In detail, the input curve does not take the shape of a pair of smooth straight lines as shown, owing to the fact that the starting resistance is cut out in a number of definite steps; the lines are saw-toothed (Fig. 396), a small peak occurring each time a fresh notch is made on the controller or by the automatic accelerating relay, and the current then dying away until the next notch is obtained. The straight lines shown represent average values, and are close enough to the facts for the purposes of the present discussion.

The quantities to be found from the graphs are the total energy consumption for the run and the peak demand due to the car. The latter has already been shown to occur during the period of constant acceleration with the motors in parallel, and is seen from the graph to be 80 H.P. or 71 kW. This figure can be calculated to an accuracy of $\frac{1}{2}\%$ by multiplying the gross T.E. in lb., by the speed at which full parallel notch is obtained, in m.p.h., and dividing by five times the efficiency per cent., giving in the case under discussion $2\,500 \times 12 / (5 \times 84)$ or, to the accuracy stated, 71 kW. The peak output required from the substations, and that finally called for from the generating plant, exceed this figure by the

* The T.E. produced by a series motor depends solely on the current, except where tapped or shunted field control is employed.

amount of the intermediate losses, depending on the layout of the system. The total energy input is given by the area under the power input curve, and amounts in this case to 0.23 kWh.* Here again, losses must be allowed for when computing the energy to be generated and converted.

To complete this example, it may be noted that as a distance of 900 ft. is covered in 50 secs., the average running speed is $900 \times 60 / 50 \times 88 = 12\frac{1}{4}$ m.p.h. With stops of 10 secs. the schedule speed would be $50 / 60 \times 12\frac{1}{4}$ or $10\frac{1}{4}$ m.p.h. The total energy input is 230 Wh and the ton-miles are $12 \times 900 / 5 \times 280 = 1.9$, giving $230 / 1.9$ or 121 Wh per ton-mile. Incidental delays increase the energy consumption both by necessitating extra starts (with their consequent losses in the starting resistances) and by the necessity of making up time later, and hence running a greater distance under power instead of coasting. The skill and care of the driver in the use of his controller counts for still more; it will be realised that the curves represent an ideal case, and that allowance must be made for this in practice.

The remarks and examples in the above paragraphs apply specifically to D.C. traction, but a good deal applies to any system. The most formidable rival of the D.C. system is the A.C. single-phase, using series-type motors whose characteristics are somewhat similar to those of the D.C. series machine. The difference in operation is that reduced volts can be supplied to the motors for starting, by means of the transformer carried on the train, thus doing away with the loss in rheostats. The 3-phase induction motor has on the contrary a shunt characteristic, and has to be accelerated up to a practically definite maximum speed—subject to the possibility of providing more than one running speed by means of a pole-changing device.

887. Energy Required per Ton-Mile.—The energy used per ton-mile under constant speed conditions is shown in the curves of Fig. 399, p. 572, based on the same data. These are more or less directly applicable to *non-stop runs*, where the energy required for acceleration is a negligible proportion of the whole. Under these conditions the curves show that the watt-hours per ton-mile vary as follows:—

* Nearly half of this energy is required for accelerating up to 12 m.p.h. and about one-sixth of it is dissipated in the rheostats.

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Level track, speed 10 to 60 m.p.h., from 15 to 60 Wh per ton-mile.									
1 % grade	"	10	"	60	"	"	70	"	120
2 %	"	"	10	"	50	"	"	140	" 165
3 %	"	"	"	10	"	40	"	"	180 " 215
4 %	"	"	"	"	10	"	30	"	" 240 " 260
5 %	"	"	"	"	"	10	"	30	" 300 " 320
(10 %	"	"	"	"	"	"	"	"	"
at 10 m.p.h., 540.)									

On such a run on a main line there would in any case be no regenerative braking during the run, but simply coasting down the very mild gradients found in this country. On a round trip the energy saved in coasting one way would go far towards balancing the extra energy required for ascending the grades on the return trip. Assuming an average speed of about 40 m.p.h., the energy consumption would be about that required for this speed on the level—say from 40 to 45 Wh per ton-mile. This estimate may be too generous—a good fault in project estimates—as few trial data are available. Some years ago Mr. Hobart gave estimates for a hypothetical non-stop run of 100 miles in 2 hours, with a 766-ton train, which worked out to only 22 Wh per long-ton-mile.

For *high-speed runs over short distances*, with rapid acceleration and frequent stops,* a separate and purposely extreme example may be worked out. Assume a multiple-unit train, with stops every half mile, running on a level rapid-transit line with a maximum speed of 40 m.p.h. ($= 58.8$ ft.-sec.), and without regenerative braking. With the acceleration usually found on such lines, of (say) $1\frac{1}{4}$ m.p.h. per sec. or 1.84 ft.-sec.², considered as uniform from the start up to the maximum speed, the time taken over acceleration will be $58.8 \div 1.84 = 32$ secs. Then the distance travelled (§ 882) will be $\frac{1}{2} at^2 = 1.84 \times 32^2 / 2$ or 940 ft. out of the total 2 640 ft. The *extra* power required for acceleration only (*loc. cit.*) is $kW = .0445 WV \times 3.1 a / E$. Taking $W = 1$; $a = 1.84$; and $E = 0.8$, this becomes $kW = 0.318 V$, or, adding 10 % for rotational energy (*loc. cit.*) $kW = 0.35 V$. Then the average power required will be $\frac{1}{2} \times 0.35 \times 40 = 7$ kW, and the energy input will be $32 \times 1\ 000 \times 7 / 3\ 600$ or 62 Wh.

This may be found by an alternative method, which may

*The energy consumption of such suburban trains is fully treated on novel lines, by M. G. Say and Prof. Parker Smith in *World Power*, Aug. 1928, p. 123.

usefully be added here. The energy stored in a 1-ton train at 40 m.p.h. ($58.8 \text{ ft.-sec.} = 2\,240 \times 58.8 / 64.4 = 120\,000 \text{ ft.-lb.}$). As 1 ft.-lb. per hour, acting for one hour = 0.000 376 Wh, the energy = $120\,000 \times 0.000\,376 = 45.1 \text{ Wh.}$ Adding 10 % for rotational energy, or 4.5 Wh, the total comes to 49.6 Wh. Then the energy input to the train will, at 80 % efficiency, be $49.6 / 0.80 = 62 \text{ Wh}$ as before.

Continuing the example, at 40 m.p.h. the curves in Fig. 399 show that about 1.8 kW per ton is required for maintaining the

TABLE 190.—*Traffic and Energy Data, 1927; Southern Railway.*

	Western Section with Waterloo and City.	Central.	Eastern.
Train-miles, loaded and empty	5 433 323	2 354 796	5 347 691
Car-miles	28 310 577	13 874 439	27 523 329
Average car-miles per train-mile	5.2	5.8	5.1
Cost of working, viz.: energy, permanent way, conductor rails, vehicles and guards	£347 118	£287 920	£433 190
Cost per train-mile	15.38d.	29.34d.	19.44d.
" car-mile	2.94d.	4.98d.	3.78d.
kWh used for traction	57 921 291	37 088 336	63 170 706
" " per train-mile	10.74	15.75	11.81
" " car-mile	2.06	2.67	2.30
Cost of generation or purchase and distribution of power for traction	£149 313	£126 133	£224 550
Cost of per train-mile	6.65d.	12.86d.	10.09d.
" " car-mile	1.28d.	2.18d.	1.96d.

steady speed. But as it would require about the same distance in which to bring the train to rest as to bring it up to speed—the two amounting to say 1 800 ft. out of 2 640, the train would merely coast the middle stretch. So the energy used is 62 Wh for 1 ton for half a mile, or 124 Wh per ton-mile. This is, of course, very high, because such a speed as 40 m.p.h. would be uneconomical on such a short run.

On the Northern Italian Railways* the average energy purchased or specially generated per ton-mile, for purely traction purposes, measured at the delivery point, is 29 Wh. The highest

* *Elec. Rev.*, Vol. 102, p. 495.

figure is 55 Wh on the Milan-Varese section, where acceleration is high and much power is used for heating; varying from 45 Wh in July to 78 Wh in January in consequence.

From a paper by E. C. Cox, read before the Institute of Transport,* the following traffic and energy data of the Southern Railway (Table 190) are taken.

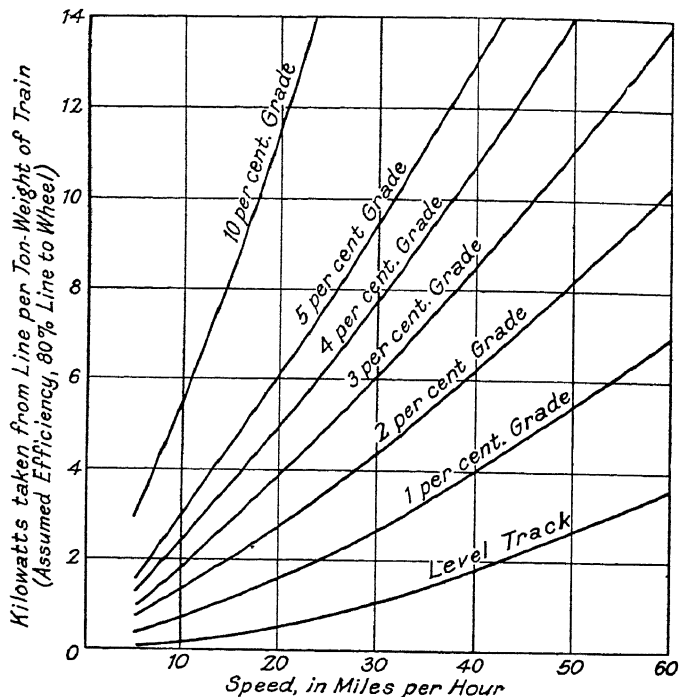


FIG. 399.—Speed and energy demand on various gradients.

888. Power and Energy Consumption on Railways.—The progressive examples in the preceding paragraphs are based on a single 8-ton tramcar on grooved rails, but the formulæ are equally applicable to a heavy train drawn at high speed by a locomotive. In this case, however, the tractive resistance will be different and less indefinite (owing to clean track), as noted in § 891. At high speeds, wind resistance ceases to be negligible, and at extreme

speeds it becomes predominant, as was found on the Berlin-Zossen line.

Using fair average values of track resistance, and an efficiency from line to wheel rim of 80 % (which could in favourable cases be increased to 85 %), the curves in Fig. 399 may safely be used for project purposes. They give the power in kW required *per ton* from the line at various steady speeds and on various gradients, assuming a straight track and no other windage than that due to the motion. From these curves the approximate power required for a train of any given weight can be read off.

Examples.—Consider a train weighing 300 tons and drawn by an electric locomotive at 30 m.p.h. on a straight road. Then, on level track, the lowest curve shows the power required to be 1.04 kW per ton, or 312 kW in all; while on a 3 % gradient it will be 6.04 kW or 1812 kW in all.

Or, again, as an extreme case, take a train of 100 tons weight travelling at 10 m.p.h. up a 10 % grade on a mountain railway; the power required will be 5.7 kW per ton or 570 kW all told. In this case, however, the question of adhesion (§ 890) comes in, and a locomotive might have to give way to a multiple unit train in order to obviate slipping.

889. Power and Energy Consumption on Tramways.—

Dealing with tramway systems, Dawson gives the data shown in Table 191:—

TABLE 191.—*Approximate Indicated Horse-Power Required per Tramway Car at a Tramway Power Station.*

Cars.	I.H.P. per car.	Cars.	I.H.P. per car.
1-5	35	15-25	20
5-10	30	25-50	15
10-15	25		

Taking into account the losses in engine, generator, and lines, a maximum demand on the generating station of 9 kW per tramway car will not be far wrong on fairly large systems (30 or 40 cars), and this may run up to 20 kW on small systems; of course spare plant is necessary in a power-house confined to the system, over and above this. A single tramcar at ordinary schedule speeds of about $7\frac{1}{2}$ m.p.h. on a moderately good road is generally reckoned to use about 2 kWh per mile, which is equivalent to an

average demand of 15 kW or 20 E.H.P. from the line. For general purposes it is more useful to assume that from 120 to 150 Wh will be required per ton-mile, according to circumstances, for any tramcar and at any ordinary speed. (On railways—see paragraph 888—the consumption is much lower.)

Figures published by the Ministry of Transport (1933) show an average consumption of 2·27 kWh per car-mile for tramways and 1·68 kWh per car-mile for trackless trolley buses.

PRACTICAL CONSIDERATIONS AND DATA.

890. Adhesion.—The familiar sight of a main-line steam locomotive trying to start a heavy train, while only succeeding in skidding the driving wheels, is due to insufficient adhesion between tyres and rails, aggravated by the uneven nature of the torque which is a feature of all reciprocating engines, especially those with a small number of cylinders. The perfectly even torque of an electric motor (other than a single-phase A.C. motor) and the possibility of having (in effect) several locomotives per train by the use of multiple-unit stock, goes far towards overcoming this trouble. In the important department of braking, where considerations both of safety and economy demand it, the principle of making full use of the total weight of the train for adhesion has been carried to the limit, and while all vehicles of a passenger train are invariably power-braked, the same practice is rapidly becoming standard in goods service. The saving in wear and tear of rails and wheels is substantial on electric lines using electric braking. In all cases the weight on each driving (or braking) wheel should be five or six times the greatest tractive or retarding effort which its rim has to exert on the rail; otherwise there is a danger of the wheels slipping. Where the gradients are very steep an even higher ratio may be advisable, as the possibility of a car running backwards downhill, or failing to answer to the brakes when running down, must be taken into account. If the rails are greasy and the wheels once start slipping the adhesion may practically disappear, in which case braking becomes ineffective and the car passes out of control. From various sources the following ratios are found for the adhesive force or tractive coefficient = $\frac{\text{weight on driving wheels}}{\text{total tractive effort}}$:—

	Normal.	Sanded.
Greasy moist rail	8-15 %.	25 %.
Wet rail .	15-20 %.	25-30 %.
Dry clean rail	20-28 %.	28 %.

For example, the question arose as to whether locomotives, motor coaches with trailers, or motor coaches only should be used on a narrow gauge hill railway having long gradients of 8 % (§ 919). In the first instance there would have been 42 tons (94 000 lb.) on the driving wheels of the locomotive, the weight of the loaded train being 87 tons. The tractive effort for an 8 % gradient would then be $87 \times 2\,240 \times 8 / 100 = 15\,600$ lb. Adding tractive effort for friction at 15 lb. per ton, 1 300 lb., brings the total to 16 900 lb. The ratio in this case was $94\,000 / 16\,900$ or $5\frac{1}{2}$, and in view of the great risks involved this was considered altogether insufficient. In the case of a train of similar carrying capacity made up of two motor coaches of 29 tons each and two trailers of 15 tons each, or 88 tons in all, the weight on the drivers was 130 000 lb.; tractive effort for gradient 8 % of 88 tons or 15 750 lb. and for friction 1 300 lb., total 17 050 lb.; tractive coefficient $130\,000 / 17\,050 = 7\frac{1}{2}$. With a lightly loaded train this factor would be reduced considerably, and with a slippery rail it was considered possible that trouble might be experienced in case it should prove necessary to start on the steep gradient, an unlikely but not impossible contingency. Using motor coaches only, the whole weight of the train would be on the driving wheels, and the coefficient would be about 11 under the same conditions. This example shows that, whilst depending on adhesion only, motor coaches and multiple unit trains of such coaches with no trailers can easily climb gradients which would be out of the question for locomotives (whether steam or electric) unless working on a rack.

891. Tractive Resistance.—In the tramway examples taken above, a constant tractive resistance of 30 lb. per ton was assumed throughout the run. For such a case this assumption is justified by the uncertain and variable condition of the track and by the lowness of the speeds. In high-speed railway working, however, no such approximation can be allowed, and the resistance to steady motion on the level will vary with the speed according to a fairly definite curve. The difficulty is to forecast what this curve will be, with any particular stock, since sufficient experimental work has

not been carried out to enable the effects of the multitude of variables involved to be separated from one another with certainty. From tests on the Lancashire and Yorkshire Railway, Aspinall* gives the following formula for finding the specific resistance to motion per ton of dead-weight, which we have called k above:—

$$k = 2.5 \{V^{\frac{2}{3}} / (50.8 + 0.0278 L)\}$$

for trains hauled by locomotives on straight level track in Great Britain. In this formula V is the speed in m.p.h. and L is the length of the train over coach bodies in feet.

892. Special Points in the Design of Distribution System and Protection.—From the point of view of conversion and distribution, a traction load has peculiarities which differentiate it sharply from industrial supply; it is used to maintain continuously alive a great length of uninsulated conductor exposed, from the nature of the case, to exceptional risks of mechanical damage and short-circuit; and it has to meet a very irregular demand for power from vehicles containing a great deal of gear packed into the minimum of space, providing a second happy hunting ground for faults. Hence it is not surprising that by comparison with other loads traction service is very severe, and abounds in opportunities for the plant and protective devices to indicate their fitness and robustness—or the reverse.†

Apart from the strain on the gear under the resulting conditions, it becomes a matter of difficulty to obtain reliable discrimination between faults and abnormal loads due to trains. The maximum voltage drop in railway practice is, for reasons of economy and on account of the comparative insensitiveness of the motors, many times larger than could be allowed in ordinary public supply (§ 469, Vol. 2), so that the ratio between short-circuit current on a distant fault and normal peak load current is much less in the former case. Where conditions are such that a single feeder may only be supplying power to one or two trains, any slight abnormality in running may throw a considerable short peak on the circuit, and it is clearly undesirable that in such a case the circuit-breakers should operate. A high enough setting to secure

* *Proc. Inst. C.E.*, Vol. 147, p. 155.

† A particular case may be cited, where a broken collector shoe on a suburban third-rail system provided over fifteen short-circuits from third rail to running rail on one feeder, all within half an hour.

this result may, however, make the breaker operation uncertain in the case of remote faults. Consequently the actual setting is in the nature of a compromise, it being generally impossible to set the breakers so as to confine trippings entirely to fault conditions. The fact of a single feeder being off load for a minute or so does not in any case cause appreciable delay in the service, since the load is taken by the substation at the other end of the section.

893. Capacity of Generating Station and Substations.—Having obtained the data giving the power required by any car or train on the system in any circumstances, the calculation of generating plant capacity becomes, as already stated, merely a matter of arithmetic. By adding together the power taken by all cars or trains at any moment, and making allowance for the transmission, conversion and distribution losses, the load on the generating station is obtained for that moment; and, by reference to the time-tables, a complete load curve can be worked out covering the 24 hours. The chief uncertainty arises over the fact that, when delays occur, the normal time-table is upset and an abnormal peak may arise due to an unusual number of vehicles accelerating simultaneously. Especially is this the case after a shut-down affecting any large proportion of the system, and a margin must be allowed accordingly.

These remarks apply, *mutatis mutandis*, to the substations also, but the diversity factor of the load will here in general be worse, owing to the smaller number of coaches supplied. It is important to realise the degree of fluctuation that may occur in the load of a railway substation, apart from the frequent short-circuits; the load on rotary converter units is never steady, but will vary from practically zero to well over full load and back again within the minute. Thus plant for this work must be designed for very large overloads; or, to put it the other way, the machine is designed to stand the peaks, while the efficiency is then kept as high as possible at low outputs.

894. Comparison of Steam and Electric Working in Heavy Railway Electrification.—In a paper read before the American Institute of Electrical Engineers some years ago, Mr. Hobart compared steam and electric locomotives for heavy main-line express service.

His calculations showed, for a *steam locomotive*, an efficiency from coal to crank-pin of 4·4 %, and from coal to draw-bar 3·53 %.

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The fuel used for steaming up, and wasted at the end of the journey, reduced the net efficiency further to 2·65 %, equivalent to a fuel consumption of 6·86 lb. per draw-bar H.P.-hr.

For the *electric locomotive* he similarly obtained an overall efficiency from coal pile to outgoing cables of 11 %. Taking into account the various losses—generating, transforming, substations, machines, transmission to train, and train equipment—the overall efficiency from coal pile to driving wheels will be

For dense service, 0·061 or 6·1 %.

„ ‘sparse express,’ 0·066 or 6·6 %.

The coal consumption was estimated to be 47 % of that required for steam working. With denser traffic and more stops electricity would have a still greater advantage over steam. Furthermore, fuel could be delivered at a cheaper rate at the power-house than on the tender, and a cheaper grade of fuel could be used, so the ratio of fuel costs would be about 3 to 1. In a paper read before the I.E.E. (*Jour.*, Vol. 52, p. 299), Mr. R. T. Smith similarly remarks that ‘the cost of coal burnt in a large modern generating station producing electricity for hauling trains by an electric locomotive is less than half the cost for doing the same work in a steam locomotive.’

(For Bibliography, see § 934 at end of Chapter 35, and § 955 at end of Chapter 36.)

ELECTRIC TRACTION; EQUIPMENT AND WORKING.

VEHICLE EQUIPMENT FOR MOTIVE POWER.

895. Tramway Motors and Rating; Gearing and Control.
 —(For motors and their characteristics generally *see* Chapters 28, 29.) Much higher acceleration is possible with electric motors than with steam engines on account of the possibility of using a number of motor coaches on one train, all controlled from one point (multiple-unit control), and thus getting the benefit of increased weight on driving wheels to cope with the high acceleration demanded; this in fact is their chief claim in connection with suburban or urban rapid-transit railways, and a valuable asset on tramways. Their uniform torque is also of great value compared with that of steam engines. It will be seen from Chapter 34 that the load on a traction motor is very variable, according to the conditions of road and speed, and it is also intermittent; even apart from actual stops, no power is taken from the line when coasting or when running downhill, while at starting and during acceleration there is a great demand for power.

Tramway motors are therefore always rated for intermittent (one-hour) working (§ 136). They are ventilated but enclosed motors, as otherwise mud and water would soon destroy them. To keep the weight down it is usual to employ fairly high-speed motors with single- or occasionally double-reduction spur gearing. On modern tramways the car wheels are usually 27 in. diam., though wheels from 24 to 33 in. may be found; the gear ratio may vary from 3·5 to 1 up to 5·5 to 1. If n is the gear ratio, d the diam. of the wheel in inches, V the speed in m.p.h., and R the motor r.p.m.,

$$V = 0\cdot002\ 98\ dR / n \quad \text{and} \quad R = 336\ Vn / d.$$

In this country D.C. is invariably used for tramways, and the general practice is to use 500-V series-wound, interpole motors

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(§ 676). In order to get increased power and adhesion and the benefit of series-parallel regulation (§ 452), two motors are used on two pairs of driving wheels; they may be of any size from about 10 B.H.P. upwards, according to the average power they will have to exert, as determined above (§ 879 *et seq.*). The following table gives the approximate full-load efficiency of 500-V tramway motors; but the losses of gearing, etc., are not included:—

TABLE 192.—*Full-load Efficiency of 500-V Tramway Motors.*

Output B.H.P. .	10	20	30	40	60	80	100
Efficiency per cent.	80	81	83	84	86	87	88
Amperes required	18·7	36·9	54·0	71·0	104·0	137·5	170·0

There are two running speeds: slow with the motors in series at starting, and full when in parallel later. Intermediate regulation, while starting and accelerating, is obtained by starting resistances (§ 718) temporarily in series with the motors. The changing of the connections is effected by the controller, which is also used to actuate the emergency brake (§ 899). In some cases the highest running speed is obtained by diverting some of the current from the field magnet coils, by means of a shunt; this, by lowering the back E.M.F. produced by the motors, lets in a greatly increased armature current, which causes the motors to accelerate until (neglecting alterations in losses) the increase in speed balances the decrease in field and the motors produce the same back E.M.F. as they did before (§ 669).

B.S. Specification No. 173 (1928) deals with the 'Electrical Performance of Direct-Current, Series-Wound Traction Motors.' Definitions are given of types of enclosure; the continuous and nominal one-hour (intermittent or 'short-time') ratings are defined; the permissible temperature rise, commutation, efficiency and testing of such motors are dealt with. A classification of insulating materials and details of temperature measurement are added. The specification keeps closely in line with the 'Rules for Traction Motors' of the American I.E.E. The British Standard Rating is a nominal one, the temperature rises specified affording a basis of comparison between motors of similar construction.

896. Railway Motors.—(See also Chapters 28, 29.) The battle of the systems as regards D.C. and A.C. motors for electric railways has as yet hardly been joined. So far, in Great Britain,

electrification is confined to rapid-transit urban and suburban lines, and for these D.C. has been used except in the case of one section of the Southern Railway; where, however, the original single-phase A.C. system is now being replaced by D.C. so as to obtain uniformity and interchangeability, rather than on the merits of the two systems. On a railway track, limitations of pressure, such as are necessary on tramways, are redundant with overhead railway work and can be relaxed for third-rail work, though it is inadvisable to go beyond a certain point on the motors themselves; a pressure of 1 500 V on the line is often used and 3 000 V is coming in. The very high acceleration possible is one of the main advantages of electric working, but it involves a great draught of power (§§ 882 and 883) and therefore a very heavy current unless high pressure is used. According to the service required, either gearing may be employed (*e.g.* for comparatively slow speed goods trains); or the motors may be mounted directly on the driving axles; or, again, the motors may be mounted on the loco frame and transmit their power by means of cranks and connecting rods, etc., after the manner of steam engines. For high-speed, main-line work the latter method is likely to become standard practice, though it involves comparatively slow speed and therefore heavy motors and reciprocating parts. The rating—whether continuous or intermittent (§ 670)—is arbitrary, and will depend entirely on the service; for non-stop trains the rating must obviously be continuous.

D.C. Traction Motors.—For D.C. working, the interpole series-wound motor (§ 676) is almost invariably used, modified in some cases to render it suitable for regenerative braking (§§ 715, 900). The various classes of service necessitate great flexibility in speed control, and the following extract is of interest:—

The widely varying speed characteristics of these services render it necessary to give very careful consideration to the motor characteristics and gear ratio, and the author would suggest that the attainment of a more flexible speed characteristic of the motor, either by partially shunting the series field of the ordinary series motor as has been suggested, or by some other means such as separate field control, is very desirable. The former method has been to some extent used, but the latter does not appear to have received the attention from designers which in the opinion of the author it deserves. (H. W. Firth, *Jour. I.E.E.*, Vol. 52, 609.)

A.C. Traction Motors.—Either single-phase or polyphase motors may be used for A.C. railway work, and each has its own merits and demerits. It will be seen elsewhere (§ 408) that while

50 cycles is the British Standard frequency, lower frequencies are generally preferable for traction work, and a subsidiary standard of 25 cycles is admitted. The majority of lines in America use 25 cycles, while in Scandinavia $16\frac{2}{3}$ cycles has been adopted. In this country, in the future, supply will generally be obtained from the general network of the country, and, if a frequency other than 50 is used on the line, frequency changers (§ 390) of some sort will be necessary in the substations.

Single-Phase Traction Motors.—For single-phase A.C. working, either the compensated series (§ 700), or the compensated repulsion (§ 703) type is generally used, single-phase induction motors as ordinarily designed having insufficient torque for this service. Of these the former, as already mentioned, is used on some American street railways where D.C. is employed on the urban and A.C. on the outlying parts of the route, the series motor working equally well on either. In place of the two running speeds * of the D.C. series-parallel system, any number of speeds can be obtained by transformer tapplings with this system, thus varying the pressure applied to the motor. Series repulsion motors, and the special designs of Latour and Déri (§ 702) have also been used. All these have practically a D.C. armature and commutator with a laminated field of special design. They all possess a variable speed-torque characteristic somewhat similar to that of a D.C. series motor.

Single-phase induction motors have been comparatively little used for traction, owing—as stated above—to insufficient torque; but it is stated that the General Electric Co. has developed a high-torque, squirrel-cage motor which, with auto-transformer starting, will give full starting torque when taking about twice the full-load current.

Polyphase Traction Motors.—With the 3-phase system on the line, 3-phase induction motors (§ 683) with constant speed characteristics are used; and, where two such are fitted on a vehicle, half-speed can be obtained by connecting them in cascade (§ 694); i.e. the rotor current of the first is passed through the stator winding of the second motor. Alternatively, or additionally, extra running speeds can be obtained by altering the number

* Running speeds as distinguished from temporary positions of the controller when resistance, not designed for more than temporary service, is in circuit.

of effective poles, by means of special windings. Either two or four speeds can be obtained in this way; for two speeds, phase-wound rotors and slip-rings are used, with resistances in the rotor circuit for starting, while for four speeds, squirrel-cage rotors and reduced-pressure starting are necessary. Owing to their flat speed characteristics induction motors cannot be used for multiple-unit working, since any irregularity, such as a slight difference in driving-wheel diameter, would cause very uneven distribution of the load between motors.

With polyphase motors regenerative control and braking (§§ 715, 900) can be, and generally is, used; but the disadvantage of requiring three instead of only two conductors is a serious one, especially at crossing and meeting points.

897. Control of Direct Current Railway Motors.—Where a single D.C. locomotive of moderate power is in question, the function of the controller is much the same as in a tramcar, except that very much heavier currents have to be dealt with. Consequently it is usual to arrange for the operation of the main controller to be effected by power from the line through the medium of an easily manipulated handle and dial showing the various positions. As the locomotive increases in size and power, the main controller becomes more complicated and its performance in breaking heavy currents more exacting, but the operating controller remains simple. In all cases should the driver let go for any reason, the knob on the top of the handle rises and the circuit is opened automatically, and the brakes are applied; hence the name, the ‘dead man’s handle’ (see further details, §§ 741, 918).

In *multiple-unit D.C. trains* each motor coach is complete in itself, with its pair of motors (or two pairs) and its main controller (which may be placed down by the motors and out of the way) and its operating or ‘master’ controller in the driver’s cabin. Any number of such coaches may be coupled together to form a ‘unit,’ the train being made up of so many units as will suit the state of the traffic. An electric control-circuit runs through the whole train, from coach to coach, leading to the parallel master controllers in each driver’s compartment. Whichever of these is for the time being in front is used, the rest being locked out of action. The function of the master controller is to operate all the separate main controllers electrically or electro-pneumatically, and simultaneously, from the driver’s seat. The operation

of starting up is generally automatic, each successive step from series plus resistance up to full parallel taking place at a predetermined current. The actual making and breaking of the main circuit is done by quick-break contactors, operated by power—electro-magnetic or electro-pneumatic as the case may be—the pneumatic method being the most favoured. A powerful magnetic blow-out is provided on the main circuit-breakers and usually for the current-breaking contactors also. If the master-controller handle is released, from accident or any other cause, the current is cut off and the brakes are applied (*see* § 921; *see also* Regenerative Braking, §§ 715, 900).

898. Control of Alternating Current Railway Motors.—*Single-Phase.*—The usual method of control for single-phase A.C. commutator motors is to vary the voltage at the main car transformer, which is arranged with as many tapplings as are required—from 3 up to 12 according to the weight of the vehicle or train. An auto-transformer is so coupled into the circuit as to prevent open circuit occurring during the transition from one voltage to another.

With repulsion motors, a brush-shifting device is employed to vary the speed, with constant excitation on the stator.

Polyphase.—As already stated (§ 896), the cascade coupling of two 3-phase motors gives half the fixed speed of the motors individually or in parallel, and the number of poles may also be changed to vary the speed. Resistances in the rotor circuit are also used for starting phase-wound machines, whether the other devices are used or not.

For squirrel-cage rotors, an auto-transformer is used for starting, sufficient tapplings being provided to ensure even acceleration.

899. Braking and Brakes.—As the speed and weight of electric vehicles increases, the question of brakes becomes ever more important; and, while the general principles are the same in all cases the application of those principles differs greatly according to the type of vehicle. Braking produces negative acceleration and, as shown in § 882, the horse-power, P , absorbed in retardation is equal to $0.186 a WV = P v / 550 = P \times 1.467 V / 550$. Therefore $P = 102.5 a W / 1.467 = 70 a$ lb. per ton of loaded vehicle. This is the total retarding force; the friction of the gearing, etc., will take up a variable amount, according to circumstances, of this, and the balance must be applied by the brakes themselves. The rate of

stopping, a , should usually not exceed 2 ft. per sec.² for the sake of the passengers' comfort. The distance run before stopping $= \frac{1}{2} at^2 = 1.08 V^2 / a$ ft. (where V is in m.p.h. and a in ft. per sec.²), and the time taken in stopping is $1.47 V / a$ secs. There are two separate and distinct uses of the brake equipment, *viz.* to control a car on an incline, so as to keep the speed within safe limits, and to stop a car, either to avert an accident or to allow passengers to alight. The disadvantage of specific accident or emergency brakes is that they are not ordinarily used and the driver may fail to use them at the critical moment.

There are many types of brake in use, and generally more than one is fitted on each vehicle; the chief varieties are the wheel brake; the rail or slipper brake; and the electric brake in one of many forms. A brake may be applied either by hand—confined to tramways—or by power: vacuum, compressed air or electricity.

With *wheel brakes* the greatest effect is obtained just before skidding occurs, but once the wheel is held altogether the brake becomes useless and must be slackened off and applied afresh; if this should occur frequently, flats on the wheel result. This is liable to happen when there is a light sludge of wet dust on the rails, and sanding is then necessary. Rim brake shoes wear out rapidly, or else wear away the wheels, which is worse, and they need constant examination to keep them efficient. This is more especially the case perhaps with new rolling stock, though it ought not to be so; bearings are too frequently ruined at the very start by trying to start up a train against maladjusted brakes which have stuck on.

On Tramways.—Generally speaking, tramcars are provided with a hand brake and an electric brake, two separate brakes being necessary and compulsory (see below for Regulation). One of the great disadvantages of the hand brake is the time taken to apply it, for a car travelling even at 10 m.p.h. goes far enough in a single second to make a difference in an emergency. The action of the hand brake is simply to press a brake shoe on the wheels or a slipper on the track, which may also be done, and much more rapidly, by pneumatic or electrical methods. American practice is for the most part in the direction of compressed-air brakes for all purposes, but there are also a number of types of electric brake on the market.

An *electric brake* proper may act in one of several ways; the action of the controller, after cutting off the line current, may connect the two motors up in parallel as self-excited series generators and cause them to retard the car by dissipating the energy generated through the starting resistance; or, may return energy to the line regeneratively (§§ 715, 900). Or, again, there may be a magnetic frictional disc brake worked by this current. In this latter case the retardation is due to three separate effects, namely, that due to the motors acting as generators, the momentum of the car supplying the power to drive them; the friction of the brake disc; and the drag due to eddy currents produced by revolution of the disc in an intense magnetic field. Again, the energy from the motors may be utilised in working a track brake, magnetic or otherwise. This is all quite independent of the line current, for the brake only comes on when the line current is off, and the regulation in the braking is effected by altering the resistance in the brake circuit. No brake depending for its action on current *from the line* is safe, as the supply may fail just when it is wanted. The action of all electric brakes depending on the motors decreases as the speed drops, which is an advantage, but *per contra* they cannot bring a car absolutely to rest or hold it on a down gradient.

The Memorandum of the Minister of Transport (taking the place of the Board of Trade requirements) lays down as regards II. Car Equipment * :—

2. (b) *Its wheels shall be equipped with brake-blocks, which can be applied by a screw or by other means, and there shall be in addition an adequate electric brake.*

NOTE.—Where for a considerable distance the gradients are 1 in 15 or steeper, the following will be added to this regulation :—

“and a track brake approved by the Minister of Transport for use on the tramways.”

An electric brake will not be accepted as adequate unless it can be applied by a step-by-step movement either of a separate brake handle, or of the controller handle only, in the opposite direction to that necessary to apply power.

On Railways.—Power-operated brakes are of course a necessity on both steam and electrically-operated railway trains and even on single motor coaches running on rails, although in some parts of the world they are, so far as freight trains are concerned,

* Regulation in italics; Memorandum in roman type.

confined to the steam locomotive, and each wagon has its own hand brake. The almost universal practice is to fit either Westinghouse air-pressure or vacuum brakes on every wheel. Where auxiliary compressors are required on each vehicle, as with air-pressure brakes, they are motor-driven. Electrical braking, as mentioned above in connection with tramcars, may also be fitted—preferably of the regenerative type (§§ 715, 900). Lines with exceptionally heavy gradients require correspondingly powerful and efficient braking systems.

Rail or slipper brakes act directly on the rails, or in the case of very steep gradients on a special rail laid between them, and they are entirely independent of the revolution of the wheels; in fact, where track brakes are used, they somewhat interfere with the use of the other brakes, as a great deal of weight is taken off the wheels, which therefore skid more readily when retarded by rim brakes. On some mountain railways a special braking track of wood is used, or, in the case of an Abt or other rack line, the rack itself is used through a band brake on the pinion drum.

900. Regenerative Braking.—On level railways there is no great advantage in regenerative braking (§ 715) to compensate for the complications of control; but as the gradients become more frequent and steeper, the recovered energy conduces more and more to economical working. Even on the Paris Metropolitan Railway, however, the saving due to regeneration amounts to ten million francs a year.* The most usual case is that of a mountain railway, where the regenerated power of a loaded descending train will largely serve to assist an ascending one; but the ideal case would be like that sometimes encountered in mining service, where a loaded descending mineral train supplies the whole power required for raising the empty wagons up the grade. In far less extreme cases the system will often pay, if the cost of energy is high, but difficulties have been experienced with this method of control, as, unless there are other cars on the line requiring power, the generators in the power-house act as motors driven by the cars, and their speed rises, and that of the car motors may then rise dangerously high also; the result of running the unloaded generators as motors will be that all the overspeed trips in the power-house will operate, and

* *World Power*, April, 1928, p. 193.

shut down the whole station. Objections to the method based on the fact that the braking is in the front only, and that the couplings are not kept in tension, have proved groundless.*

American experience definitely lays it down that regenerative working adds to safety in running down steep grades, provided that the line is not so short that there may be no train requiring power on it while energy is being pumped into the line. On the Valtellina railway, special resistances were at one time used in the power-house to absorb any unwanted regenerated energy. The saving of power on the Chicago, Milwaukee and St. Paul railway amounts to no less than 14 % † as the result of the system.

With direct current :—Much experimental work has been done with shunt-wound D.C. motors for traction service, and scores of patents have been taken out for regenerative systems of this nature; but the aptitude of these motors for the purpose is more than counterbalanced by their disabilities in ordinary running. Series motors, as generally employed, cannot be used regeneratively; but they have of late been built with extra field windings, so that they can be temporarily converted to regenerative shunt-wound generators for braking purposes. This involves additional contactor gear on the controller also, together with separate excitation, so that it becomes a business question whether the value of the energy saved will compensate for the extra capital charges and the less simple circuits (*see also* § 718).

With alternating current :—Where 3-phase induction motors are used they can return electrical energy to the line when coasting downhill, and as the rotors cannot run more than about 4 % above the synchronous speed (§ 679) this is a safe and economical method of braking. No additional control gear is necessary, nor any extra notches on the controller, the same ones serving for both power and braking—since the synchronous speed is the determining factor; this applies both to parallel and cascade working. The method has found extensive application in the U.S.A. and on the Continent, and shows a very high efficiency. Thus on the Giovi line (Italy), with trains running at 45 km. per hr. on a 3.5 % gradient, the energy consumption for a train climbing only was

* *See also* 'Tramway Regenerative Braking,' *El. Rev.*, Vol. 102, p. 1040; and 'Tramway Regenerative Control,' *ibid.*, Vol. 112, p. 340.

† *General Electric Review*, Nov., 1920, p. 879.

found to be 30·8 Wh. per ton-mile as against 13 to 14½ Wh per ton-mile with trains ascending and descending simultaneously.

Regenerative braking is also used on single-phase lines in Switzerland. This involves no additional gear on the controller, but extra windings are provided in parallel with the commutating poles.

EQUIPMENT: PERMANENT WAY AND RETURN CIRCUIT.

901. Rails and Permanent Way ; Tramways.—On electric tramways, grooved girder rails laid on a concrete foundation are the general rule. Step girder rails have been used to some extent but they interfere with the ordinary traffic too much ; they offer less tractive resistance than grooved rails ; and T rails, which are generally used in America, offer still less. The wear and tear on electric tramway rails is very much greater than that on the old horse-drawn or cable tramways, or than that on railways—a fact discovered by very dearly-bought experience in the early days of the art, when utterly insufficient amounts were set aside for depreciation, not only by local authorities, but even by companies. Not infrequently the rails became unfit for use in three years or even less, before the advent of modern special steels (see next paragraph).

The cause of excessive wear is chiefly the unsprung loads of the motors, especially where geared direct to the axles, and (in the case of tramways) the use of the track by other traffic. Owing to this rapid depreciation, very heavy rail sections are used, from 90 to 120 lb. per yd. Fishplates are used in British practice, and the rails are kept to gauge by a steel tie bar. British Standards Institution Specification No. 2 (1927) deals with 'Tramway Rails and Fishplates,' dimensioned drawings of six types being given. Amongst the more important matters dealt with in this exhaustive specification are the quality and composition of the steel ; falling weight, tensile and bending tests ; holes and slots ; and permissible variations in weight and dimensions.

At curves the grooves have to be wider than on the straight, and spiral transition 'easement' curves are used to ensure the car entering and leaving easily. With ordinary road construction correct super-elevation of the outer rail is of course impracticable, so speed has to be reduced when turning. The reduction in power

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on this account to some extent counterbalances the excessive friction on curves.

In the 'Memorandum Regarding Details of Construction of New Lines and Equipment' issued by the Minister of Transport (1926), which apply also to reconstructed lines, the following requirements as to the permanent way occur under the heading: I. Constructional Details:—

(C) PERMANENT WAY.

(1) The weight of rails, on public roads, should not be less than 90 lb. per yard, and one or other of the British Standard sections for Tramway Rails is preferred.

(2) The groove of new rails must not exceed one inch and one eighth in width, but a groove not exceeding one inch and one quarter will be accepted on curves of less than 150 ft. radius, and for special work.

(3) The removal of storm water accumulating in the rail groove to be adequately provided for by slotted rails, or other approved device, suitably connected to the drainage system. The number of 'draw-off' points to be increased on gradients or at termini.

(4) The details of permanent way and mode of construction in the case of new lines should be submitted to the Minister of Transport for approval before work is commenced, and may not be substantially varied at any time without the Minister's consent.

The 'British Standard Method of Specifying the Resistance of Steel Conductor Rails' is referred to in paragraph 920. The resistance of one yard of an ordinary carbon steel track rail of 100 lb. weight per yd. is approximately $0\cdot000\ 027\ \Omega$; or $(4\cdot83 / \text{lb. per yd.})\ \Omega$ per mile. (*Cf.* §§ 902 and 920.)

The weight in lb. per yd. of any steel rail = the cross-sectional area in sq. in. $\times 10\cdot2$.

Another B.S. Specification, No. 79 (1927), deals with 'British Standard Trackwork for Tramways,' i.e. with turn-outs, cross-overs, junctions, crossings, points and interlacing tracks for every variety of construction used in practice, with diagrams, dimensions and standard arrangements for holing.

With clearances between rails, and between the line and the kerb, posts, etc., we are not here concerned.*

902. Rails and Permanent Way; Railways.—On British electric railways, ordinary permanent way construction is adopted, with heavy rail sections mounted on chairs and timber sleepers, but bonded for the return circuit (§§ 903 and 904). With the even

* See 'Memorandum Regarding Details of Construction, etc.' (Tramways and Light Railways Laid on Public Roads). Ministry of Transport (1926).

torque of a motor, the wear and tear should be, and probably will eventually be, less than with steam working; but hitherto it is understood to have been otherwise. Whereas a life of 12 or 15 years is not uncommon on main steam lines, the life of rails has so far been only about half this on electric railways, and as low as three years in tunnels. In the case of the Metropolitan Railway, London, a remedy was found in the use of a specially hard silicon steel, made by the Sandberg process; high-silicon basic open-hearth and high-silicon acid Bessemer being considered the best. These do not rust seriously and are superior to nickel, chrome, and other special steels. Reference, however, to paragraph 979 on 'ferro-alloys' will show that new steels are being developed every year with special properties for special work—*e.g.* the Hadfield and other steels for points, etc. The composition of one of these special steels is as follows: * manganese 11 to 13 %, carbon 1 to 1.2 %, silicon 0.4 %, sulphur 0.05 %, phosphorus 0.08 %. The resistance of this steel is about $3\frac{1}{2}$ times that of carbon steel and 38.5 times that of copper, and these figures are not greatly affected by the proportion of *Mn* within the above limits. One yard of rail, of 100 lb. per yd., of the above special steel, has a resistance of 0.000 096 Ω , a current of 250 A. giving a drop on 20 ft. length of 0.16 V; or 1 volt per 40 yds. neglecting the bonding resistance (*cf.* §§ 901 and 920.)

903. Rails as Return Circuit; D.C. Tramways.—On D.C. tramways (for A.C. see § 905) the rails are now invariably used as the return circuit for the energy supplied to the cars, † the connection to the motors being made through the frame and wheels. The two rails, or on a double track all four rails, are in parallel for this purpose, and are connected to the negative pole of the generator. The rails are in contact with the general mass of the earth and constitute an uninsulated 'earthed return.' Now the term 'earth' gives rise to a great deal of misunderstanding, owing to the confusion between *earth* returns and *earthed* returns. For telegraphic and telephonic work the earth itself is often used to complete the circuit in place of a return wire; that is to say, there is a real earth return. But in the worst constructed electric tramway of early days, the rails were at least intended to act as the return, while in the best-constructed modern systems, in which

* *Edgar Allen News.*

† Except in the conduit system, and near observatories.

an uninsulated return is used, there is very little current carried by the general mass of the earth; the rails are rendered electrically continuous for this purpose. The current will naturally take the best conducting path, so, though the rails and the return are at the same potential as the earth, the latter is not appreciably used as a return; there is an earthed, and not an earth, return. Just as a telephone system may have either complete metallic circuits or a metallic lead and an earth return, so can an electric traction system have either a double insulated metallic circuit or a metallic insulated line and an earthed return. Both methods have been adopted in one place or another, and each has advantages of its own: the former in that troubles from interference with other people's property or circuits are avoided, the latter for its simplicity and lower cost of construction.

With an earthed return it is always possible for the current to stray into other conductors in the neighbourhood—such currents are aptly called 'vagabond'—and for this reason it is necessary to keep the resistance as low as possible. The weak point is at each rail joint, and it is therefore necessary either to weld or cast-weld the joints, making the whole line electrically continuous, or else to bridge over the fishplates with heavy copper bonds.

Even where the rail joints are welded (which may be done electrically or by the Thermit process) a bond is placed across the weld; for fishplate joints, two bonds are used, on the inside, often of 4/0 copper (or equivalent stranded) which have larger terminal lugs expanded into freshly made holes in the rail flange. There are many types of bond on the market, but the flexible types are preferable to the solid because of the severe vibration to which they are subjected. (*See footnote to paragraph 907.*)

Technical details of iron and steel when used as conductors will be found in the preceding paragraph and also in paragraph 64 (Vol. 1); but the latter figures refer rather to the conductor third-rail (§ 920) than to the running rails. In the latter, long life is more important economically than low resistance, and (as mentioned in § 902) special steels of far higher resistance are often used; always for points and crossings, etc. It may be repeated here that the weight in lb. per yd. of any steel rail = the cross-sectional area in sq. in. $\times 10.2$. The resistance in ohms per mile of single rail (ordinary carbon steel track rail) is approximately (4.83 / lb. per yd.) or (0.473 / section in sq. in.), but there are

wide variations, and the joints, in old track, increase the value greatly.* The two or four rails are always 'cross-bonded' at intervals, as this reduces the effect of bad joints by offering alternative paths to the current. With two or four rails in parallel the resistance is $\frac{1}{2}$ or $\frac{1}{4}$ of the value given by the above formula (§ 448). There are many types of bond on the market, but when old track is opened up it is generally found that a good many have ceased to fulfil their function through breakage or working loose.

It will be convenient here to give the Regulations made by the Minister of Transport (§ 1052) relating to the track and return circuit on tramways:—

3. Where any rails on which cars run or any conductors laid between or within 3 ft. of such rails form any part of a return, such part may be uninsulated. All other returns or parts of a return shall be insulated, unless of such sectional area as will reduce the difference of potential between the ends of the uninsulated portion of the return below the limit laid down in Regulation 7.

4. When any uninsulated conductor laid between or within 3 ft. of the rails forms any part of a return, it shall be electrically connected to the rails at distances apart not exceeding 100 ft. by means of copper strips having a sectional area of at least $\frac{1}{16}$ sq. in., or by other means of equal conductivity.

5. (a) When any part of a return is uninsulated it shall be connected with the negative terminal of the generator, and in such case the negative terminal of the generator shall also be directly connected, through the current-indicator hereinafter mentioned, to two separate earth connections, which shall be placed not less than 20 yds. apart.

(b) The earth connections referred to in this regulation shall be constructed, laid, and maintained so as to secure electrical contact with the general mass of earth, and so that, if possible, an E.M.F. not exceeding 4 V shall suffice to produce a current of at least 2 A from one earth connection to the other through the earth, and a test shall be made once in every month to ascertain whether this requirement is complied with.

(c) Provided that in place of such two earth connections the Company may make one connection to a main for water supply of not less than 3 ins. internal diameter, with the consent of the owner thereof and of the person supplying the water, and provided that where, from the nature of the soil or for other reasons, the Company can show to the satisfaction of the Minister of Transport that the earth connections herein specified cannot be constructed and maintained without undue expense, the provisions of this regulation shall not apply.

(d) No portion of either earth connection shall be placed within 6 ft. of any pipe except a main for water supply of not less than 3 ins. internal diameter which is metallically connected to the earth connections with the consents hereinbefore specified.

* See B.S. Specification No. 68 (1914): 'Steel Conductor Rails, Method of Specifying the Resistance of' (§ 920). Also cf. §§ 901 and 902.

(e) When the generator is at a considerable distance from the tramway the uninsulated return shall be connected to the negative terminal of the generator by means of one or more insulated return conductors, and the generator shall have no other connection with earth; and in such case the end of each insulated return connected with the uninsulated return shall be connected also through a current indicator to two separate earth connections, or with the necessary consents to a main for water supply, or with the like consents to both in the manner prescribed in this regulation.

(f) The current indicator may consist of an indicator at the generating station connected by insulated wires to the terminals of a resistance interposed between the return and the earth connection or connections, or it may consist of a suitable low-resistance maximum demand indicator. The said resistance, or the resistance of the maximum demand indicator, shall be such that the maximum current laid down in Regulation 6 (i) shall produce a difference of potential not exceeding 1 V between the terminals. The indicator shall be so constructed as to indicate correctly the current passing through the resistance when connected to the terminals by the insulated wires before-mentioned.

6. When the return is partly or entirely uninsulated the Company shall in the construction and maintenance of the tramway (a) so separate the uninsulated return from the general mass of earth, and from any pipe in the vicinity; (b) so connect together the several lengths of the rails; (c) adopt such means for reducing the difference produced by the current between the potential of the uninsulated return at any one point and the potential of the uninsulated return at any other point; and (d) so maintain the efficiency of the earth connections specified in the preceding regulations as to fulfil the following conditions, viz. :—

(i) That the current passing from the earth connections through the indicator to the generator or through the resistance to the insulated return shall not at any time exceed either 2 A per mile of single tramway line or 5 % of the total current output of the station.

(ii) That if at any time and at any place a test be made by connecting a galvanometer or other current-indicator to the uninsulated return and to any pipe in the vicinity, it shall always be possible to reverse the direction of any current indicated by interposing a battery of three Leclanché cells connected in series if the direction of the current is from the return to the pipe, or by interposing one Leclanché cell if the direction of the current is from the pipe to the return.

The owner of any such pipe may require the Company to permit him at reasonable times and intervals to ascertain by test that the conditions specified in (ii) are complied with as regards his pipe.

7. When the return is partly or entirely uninsulated a continuous record shall be kept by the Company of the difference of potential during the working of the tramway between points on the uninsulated return. If at any time such difference of potential between any two points exceeds the limit of 7 V, the Company shall take immediate steps to reduce it below that limit.*

8. Every electrical connection with any pipe shall be so arranged so to admit of easy examination, and shall be tested by the Company at least once in every three months.

* It was authoritatively laid down many years ago that the 7 V drop between any two points is *not* intended to be used as a limiting figure to work up to, but as one indicating serious danger of electrolysis.

9. The insulation of the line and of the return when insulated, and of all feeders and other conductors, shall be so maintained that the leakage current shall not exceed one hundredth of an ampere per mile of tramway. The leakage current shall be ascertained not less frequently than once in every week before or after the hours of running when the line is fully charged. If at any time it should be found that the leakage current exceeds $\frac{1}{2}$ A per mile of tramway the leakage shall be localised and removed as soon as practicable, and the running of the cars shall be stopped unless the leak is localised and removed within 24 hrs. Provided that where both line and return are placed within a conduit this regulation shall not apply.

10. Any insulated return shall be placed parallel to and at a distance not exceeding 3 ft. from the line when the line and return are both erected overhead, or 18 ins. when they are both laid underground.

(For further regulations see § 1052.)

904. Rails as Return Circuit; D.C. Railways.—The previous paragraph, relating to tramways, is equally applicable to the return circuit of railways; but the conditions are somewhat different. Instead of being buried level with the ground, the railway track is raised on chairs, and only in contact with comparatively clean ballast, through which any water percolates; and there is no mud to contend with. Furthermore, the rail joints and bonds are accessible without pulling up the permanent way, so that they can be examined regularly along with the track itself.*

The rails on railways are never welded up solid, as they are fully exposed to the heat and the cold and must be able to expand and contract freely; and, as the fishplate contact is a thoroughly inefficient electrical contact, the conductivity of the return circuit depends on the efficiency of the bonds between rails and between tracks. Lacking the support of the concrete or setts of a tramway line, and carrying heavier loads at higher speeds, the bonds are subject to far greater vibration and need constant examination (*see also* footnote to § 907). The bonds are sometimes fixed to the web of the rail, as with tramways, or they may be placed on the under side of the lower flange, as on the conductor rails of the Southern Railway.

* The present writer happened to be in the neighbourhood of a very serious accident on an American line some years ago. Track signalling was used, the working being steam, and the cause was put down as being due to a rail having been pulled away by means of a wire by some miscreant. But the rails were spiked directly on to the sleepers (*i.e.* without chairs, which are seldom used there); the sleepers were mostly rotten; and about one spike in five could be pulled out with the finger and thumb over a mile of track examined. Fortunately, inspection on this side is more thorough—as a rule.

There are at present no Ministry of Transport or other regulations dealing with electrical working on railways, other than 'tube' and 'light railways'; but the requirements of those prescribed for tramways (§ 903) are applicable technically and are generally complied with.* It should be repeated here that the limit of 7 V drop between any two points in the uninsulated return (Regulation 7 in the preceding paragraph) is not intended to be a figure up to which it is safe to work, but rather a figure indicating serious danger of electrolysis; but in railway work the maintenance of the return circuit is much easier than on a tramway line.

For 'railways constructed underground in metal-lined tunnels,' commonly known as 'tube railways,' there are regulations very similar to those printed in the preceding paragraph; but the following extracts relate to new matters, or points expressed differently:—

5. When any part of a return is uninsulated it shall be connected with the negative terminal of the generator, and in such case the negative terminal of the generator shall also be directly connected to the iron or other metal plates forming the lining of the tunnels, unless this lining is otherwise connected to the rails. In each case the connection shall be made through a suitable current indicator.

6. The iron or other metal plates forming the lining of the tunnels shall be so made and connected together as to form a continuous metal tube.

7. Where any pipe is brought into the tunnel from outside, except any pipe belonging to the Company which is not in metallic connection with or laid within 6 feet of any other pipe, means shall be provided to secure that no portion of the pipe outside the metal tube shall be in metallic connection with the tube or with any conductor of electricity within the tube.

8. When the rails form any part of the return they shall either be electrically connected, at intervals not exceeding 100 yards, to the metal tube by metallic conductors which will not be appreciably heated by a current of 100 amperes, or they shall not be in any metallic connection with the metal tube except by means of the connections to the negative terminal of the generator. In the latter case the rails shall be supported by sleepers of wood, and they shall be of such sectional area and so connected at joints and from one line of rails to another, and where necessary to supplementary conductors or feeders, that the difference of potential between the

* The Final Report of the Advisory Committee of the Ministry of Transport on the Electrification of Railways recommends that, on the evidence and in view of the practical difficulties attending the imposition of a definite limit: '(i) It is not desirable that regulations should be issued to limit the drop of potential in an uninsulated conductor on electrically operated railways; (ii) In cases where it is found impossible to dispense altogether with the present obligations which are imposed upon railway companies by the protective clauses inserted by the Board of Trade and other authorities into the Acts of the companies, these obligations should be specified definitely in each particular case.'

rails and the metal tube shall not in any part and under any working conditions exceed 10 volts. A test shall be made at least once in each month.

9. When the return is partly or entirely uninsulated a daily record shall be kept by the Company of the difference of potential during the working of the railway between any two points of the uninsulated return at the time when the load is greatest. If at any time such difference of potential exceeds the limit of 7 volts, the Company shall take immediate steps to reduce it below that limit.

10. Every line and every insulated return shall be constructed in sections, and means shall be provided at or near each station for breaking the connection between sections.

11. The leakage current shall be tested daily before and after the hours of running with the working pressure and duly recorded. Should the amount of this at any time appear to indicate a fault of insulation, steps shall at once be taken to localise and remove it.

The remarks in the preceding paragraph (tramways) as to rail resistance and special steels used for points, crossings, etc., are applicable to the railway return circuit also; and the increased resistance of special steels naturally becomes more important as the current increases. (*See also* § 920 : third-rail system.)

905. Rail Returns for Alternating Current.—Where alternating current is used for traction, the ohmic resistance of the rails is not the only factor to be considered; the drop in volts owing to inductance (§ 35) and 'skin effect' (§ 38) may be ten times as great as with continuous current, where ohmic resistance alone comes in, and it increases with the frequency of the supply. Transformers have also been used in A.C. traction in a somewhat similar manner to the negative boosters described in paragraph 906. (*See also* §§ 142, 389, 395.)

At 25 cycles it is safe to assume that the drop in volts in the rails will be about 6·5 times that due to a continuous current of the same ampere or R.M.S. (§§ 25, 56) value. A supplementary return conductor, connected to the rails at frequent intervals, confines the serious drop to the sections of the line where the traffic for the moment happens to be. The drop in such a conductor, of copper, is not more than $1\frac{1}{2}$ times what it would be with continuous current—for the skin effect decreases with the diameter of the conductor, and the latter is only about $\frac{5}{16}$ as large for a copper feeder as for an iron wire (of track-rail steel) of equal ohmic resistance; on the other hand, the skin effect is somewhat smaller in an iron rail than in an iron wire of equal section, because, for a given sectional area, the skin effect decreases as the perimeter increases.

Skin effect has hitherto been neglected, as it is of little importance in the ordinary applications of electricity; but with very large conductors, and especially steel rails, it is a factor of serious importance. The following extract from an article by Dr. D. K. Morris will therefore be useful:—

Alternating currents, especially of high frequency, are by their inductive action to some extent confined to the surface of solid conductors. The increase of ohmic resistance due to this cause is separate from the *apparent* increase due to impedance. With ordinary frequencies the effect is negligible in conductors less than $\frac{1}{2}$ inch in diameter of non-magnetic material.

From the tables given by this writer the increase of resistance in copper, due to skin effect, at the standard frequency of 50 periods, is

Diam. 0.59 in.—Increase 0.2 %.	Diam. 0.98 in.—Increase 7 %.
0.79	2.7
	1.57
	33

In steel rails the increase is much greater, and Dr. Morris quotes the following figures, given by Mordey and Jenkin, relating to the relative drop in volts with D.C. and A.C. In single track, laid with 90-lb. rails:—

Current Density.	Volts Drop Per Mile.		
	D.C.	A.C., 15 Cycles.	A.C., 42 Cycles.
56.5 A per sq. in.	21 V	120 V	210 V
39.5 "	14	66	112
28.2 "	11	39	67
16.9 "	6	21	34

906. Return Feeders and Boosters.—Where the length of line or density of traffic is very great the large current in the rails may involve too great a drop in pressure in them; for the higher the drop, the greater is the chance of leakage and corrosion in the neighbourhood. Whereas in ordinary circuits the loss of volts in the lead and return are about equal, the conductors of a tramway are so designed that nearly all the drop is in the lead, *i.e.* the feeders and overhead line; the drop in the return circuit is limited by Regulation 7 (§ 903) to 7 V in Great Britain. If the drop on the bonded rails alone would otherwise be greater than this, insulated copper return feeders are taken from suitable points back to the generating station; and, if necessary, a motor-generator

or 'negative booster' (or, for A.C., a transformer) is connected in this feeder to neutralise the excess drop in volts. The use of motor-generators or boosters in electric traction work is twofold: they may be used in the ordinary way, with the auxiliary generator in series with the feeders or line, transmitting the full current and adding to the pressure (Fig. 93A, § 389, Vol. 2); or they may be used in the negative feeder (Fig. 94, § 389, Vol. 2), to suck the current back from the rail circuit at distant points on the system, and thus reduce the fall of potential on the uninsulated circuit to proper limits. For example, a return or negative feeder will be run from a meeting-place of many tracks, and will there be connected to all the rails. Naturally the return current will go back to the station by that feeder in preference to the higher resistance rails, and if there is a generator (motor-driven) connected in the power station between the negative bus-bar and the end of this feeder, so as to force a heavy current back to the negative bus-bar, the effect of the negative feeder is increased. Using a negative booster is equivalent to reducing the resistance (or increasing the conductivity) of the return circuit and feeder; and if this resistance were zero no booster would be needed.

It is unsafe to operate a group of separate feeders from a common booster owing to the risk of abnormal pressure rise at the feed point of a temporarily lightly loaded section, and although, by parallel operation of the feeders, this risk may be avoided, the practice leads to unequal distribution of the load amongst the feeders, the shorter one being overloaded. For satisfactory operation, therefore, a separate booster ought to be installed in each long and heavily loaded feeder. In order, however, to avoid the installation of a large number of boosters of varying capacity, the authors would suggest that advantage be taken of the method already described of employing main feeders, each having several short sub-feeders. The pressure drop in the main feeder alone would be compensated by the booster, so that the sub-feeder would be maintained at a constant potential, the design of the sub-feeders being governed by considerations of overheating alone, and their load fluctuations not materially affecting the pressures at the feed points.

The general use of negative boosters alone permits of the attainment of the two ideal conditions, *viz.* :—

1. Uniform absolute potential at the negative feed points and hence no interchange of vagabond current.
2. Minimum length of sub-section, and hence minimum vagabond current.

Further, full advantage is taken of the high conductivity of the track; the rail drop is easily maintained at a low value; the pressure loss in the negative feeders is no longer subtracted from the supply pressure; great potential difference between the negative bus-bar and earth is avoided, and, finally, with heavy loading a very material reduction may be obtained in the amount of return copper as compared with the amount required to obtain satisfactory conditions, even if

they could possibly be obtained, without boosters. The saving in cost over the installation of additional sub-stations would be very considerable. (J. G. and R. G. Cunliffe, *Jour. I.E.E.*, Vol. 50, p. 703.)

While a positive (or line) booster has a self-excited series generator, a negative (return feeder) booster is separately excited by a coil connected in series *with the line*, so that the negative 'suction' increases with the load in the line. The armature of the latter is of course connected in series with the feeder.

907. Electrolytic Corrosion.—The principles of electrolysis are explained in § 127, Vol. 1, and § 970, and many examples will be found in Chapter 38 on 'Electro-chemical Processes' of the benefits conferred by it on humanity. But, like most other beneficent things, electrolysis has a maleficent side to it when not under proper control. Most substances—and metals especially—are liable to corrosion when buried in the ground, from the chemical effects of acids or alkalis in the soil, and from other causes.* When 'vagabond currents' are present to assist the process, it is greatly accelerated. In the case of tramways with an 'uninsulated return'—this is the official phrase—if there is leakage from the rails to other metallic bodies in the neighbourhood, and then back to the rails or the power station, corrosion takes place through electrolysis at every point where the current *leaves the metal*; in the early days of electric traction much damage was done to gas and water pipes, cable sheathings, and even steel bridges, through this agency. Lead and iron or steel are the chief victims, because they are the metals most commonly used underground; and the most important, because of their extensive use in public utility undertakings.† At the anode about 75 lb. of lead or 20 lb. of iron will be corroded by 1 A flowing for a year (Bartholomew, *Loc. cit.*).

* O. Haehnel (vide *résumé* in Science Abstracts, 1925, No. 750) calls attention to 'a novel form of intercrystalline corrosion' of lead sheathings (*see* § 553) causing them to crack or even to fall to powder, which he attributes to the effects of mechanical high-frequency vibration on an assumed allotropic form of the metal. The addition of tin and antimony (*see* footnote to § 552) reduces the liability to this form of corrosion, but increases that to chemical corrosion—and therefore, no doubt, to electro-chemical also. Where vibration is severe, as on bridges, etc., the above author suggests either suspension or a suitable bedding to damp out vibrations.

† The Post Office Engineering Department has issued a useful brochure on 'Electrolytic Action on Cable Sheaths' amongst its 'Technical Pamphlets for Workmen.' *See also* 'The Electrolysis of Lead-Covered Cables,' by S. C. Bartholomew (*El. Rev.*, Vol. 92, pp. 432-433).

By way of cure, or rather partial prevention, it is the universal practice, enforced by Regulation, to connect the positive pole of the generator * to the line and the negative to the rail return, as this confines the tendency to damage from electrolysis to the rails themselves, and the lead sheathing of the return feeders, pipes, etc., in the immediate neighbourhood of the station. Each of these can by proper construction be protected almost entirely.

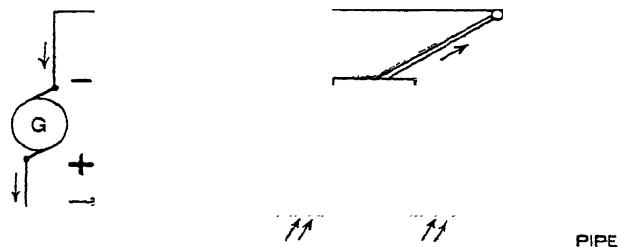


FIG. 400.—Diagram of earth return currents with rails connected to the positive pole of the generator.

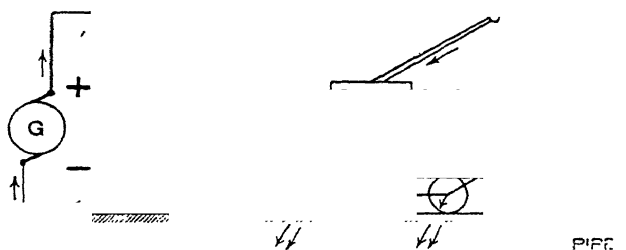


FIG. 401.—Diagram of earth return currents with rails connected to the negative pole of the generator.

Electrolytic corrosion takes place at the point where the current leaves the pipe or rail: at the point, that is to say, which is

* See Regulation 5 (§ 904). For many years every company or local authority owning a system of pipes represented to Parliament the necessity of special protective clauses for their systems in any Tramway Order in their area; and finally the whole question was thrashed out by Lord Cross's Joint Select Committee of 1893 on 'Electric Powers (Protective Clauses).' The preamble to the present Regulations for tramways (§ 1052) refers particularly to 'corrosion and injurious electrolytic action' on pipes, structures and substances, which the Regulations are designed to prevent; but in several cases special protective clauses have nevertheless been inserted in Tramway Orders. (See 'Wills' Electric Lighting.')

positive to the earth. Now, if the positive pole of the generator were connected to the rails and to earth, the tendency would be for a considerable proportion of the current to take the earth-path near the power station, to run along water and gas pipes, and to leave them for the rails again at all points where cars were running near them, thus causing corrosion over a wide area (*see* Fig. 400). If, on the other hand, the rails are made negative at the generators (as in Fig. 401), the tendency is for the general leakage to be *from* the rails (which will suffer corrosion) *to* all the pipes along the track, which then carry the current to the neighbourhood of the power-house, where it leaves them again to get to the generators; and, if at these near points copper conductors are run to the pipes, they will take the current back and prevent it going to earth and causing corrosion even near the power-house. But, even so, if the leakage is not very small corrosion will occur at every separate joint in the pipes, where the resistance is naturally much higher than in the body of the pipes, the current taking an earth-path round the joint. Where gas and water mains run near one another there is a tendency to leakage from the gas to the water pipe if both are carrying current, the resistance of the joints being higher in the former. Mr. Wedmore (*Jour. I.E.E.*, Vol. 50, p. 722) estimates the average specific resistance of the earth to be about 50 Ω per cu. yd.; and he further discusses whether the earth virtually short-circuits a pipe buried in it or whether the pipe is the better conductor. In the case of iron pipes he inclines to the former view; with lead pipes, to the latter.

The Post Office Pamphlet, referred to above, sums up the precautions which can be taken by the owner of the buried metal work as follows:—

- (a) Cables should be kept as far away as reasonably practical from tramway lines.
- (b) Contact with the rails either directly or indirectly must be avoided in the 'negative area.' Connections in the positive area may be allowed in special cases after careful investigation, as an alternative to (h).
- (c) Pipes should not be laid in contact with tramway standards.
- (d) Cables should be kept clear of water in boxes and manholes, and dry duct lines are desirable.
- (e) Chemical composition of fluid and soil has an important bearing. Cables should be liberally covered with petroleum jelly when being drawn in.
- (f) Voltage tests indicate danger points.
- (g) Measurement of strength of current in the sheathing is of great importance.
- (h) Earth plates should be sunk to which cables (and pipes if concerned) should be connected, at boxes near the points where the current leaves the cables.

(j) Iron pipes should be bonded at boxes and manholes.

(k) At the junction of routes, the cables and pipes should be joined together by lead strips soldered to the sheathing.

908. Interference with Telegraph Lines, etc.—Until electric tramways were started the telegraph and telephone circuits held a virtual monopoly in the use of the earth as a return circuit; this monopoly, however, has not been upheld by law.* Where an earthed rail return is used, telephones, telegraphs, electric signalling apparatus, and magnetic instruments may be injuriously affected in their working.† This is not the case with accumulator traction, or with a completely insulated metallic return, but these systems of traction are little employed. Telephone lines using the earth as return and mounted parallel to a tramway for any considerable distance are affected by the latter unless they are a sufficient distance away from it. The momentary breaks in the traction circuit on line and return (at the collecting gear and wheels respectively) cause buzzing in the telephones by induction, and render it impossible to hear properly; a short-circuit will cause all the indicators in the exchange to fall (where that system of ‘calling’ is employed), and will make working impossible. Where single-phase A.C. traction has been used on the line, there is also interference from electro-magnetic and electro-static induction, and the expense of adequately guarding against this is very serious (§ 926).

The remedy lies with both parties to a certain extent. The smoother the collection of the current, and the better the construction, the less trouble there will be from induction and leakage;

* The leading case is that of the East and South African Telegraph Co. v. Cape Town Tramways Co., which was decided by the Privy Council in 1902. It was there held that the owners of sensitive apparatus, such as a telegraph cable, cannot in the absence of special legislation create for themselves, by reason of the peculiarity of their apparatus, a higher right to limit the operations of their neighbours than belongs to the ordinary owners of land, who do not trade with telegraph cables. (Reference should be made to the full report in ‘Wills’ Electric Lighting.’)

† See footnote to preceding paragraph, *re* protective clauses. The Regulations (*passim*) are designed to secure such protection as can be afforded without prohibiting the almost universal practice in electric traction. As to magnetic observatories, a considerable agitation was at one time raised because of the danger to the continuity of the Greenwich records, if it should prove necessary to remove the instruments elsewhere, and a special clause was inserted in Tramway Orders.

Rail and / or road traction systems sometimes interfere with radio reception. Such trouble is specially liable to occur where powerful receiving sets are used near tramway or trolley bus-routes.

and by diverting the telephone lines out of parallelism or removing them to a distance, the effect can be still further reduced, so that tramway companies often arrange to do this. On the other hand, no trouble at all will be experienced where the telephones use a complete and twisted metallic circuit, as this will be equally unaffected by induction or leakage; such a system is far preferable in every other way, and all modern telephone systems are so arranged. The one disadvantage, apart from cost, is the extra number of wires involved.

The Regulations of the Minister of Transport (§ 1052) quoted in paragraph 903 *supra* as regards the return circuit generally, also deal with this matter as follows:—

12. The Company shall so construct and maintain their system as to secure good contact between the motors and the line and return respectively.

13. The Company shall adopt the best means available to prevent the occurrence of undue sparking at the rubbing or rolling contacts in any place and in the construction and use of their motors and generators.

EQUIPMENT: THE OVERHEAD SYSTEM ON TRAMWAYS.

909. The Overhead Trolley Wire; Tramways.—The overhead line, by which energy is conveyed to the cars, consists usually of hard-drawn high-conductivity copper wire from No. 2/0 up to No. 4/0 S.W.G., or sometimes, for heavy traffic, of silico-bronze or cadmium copper. The wire may be of 'figure-of-eight' cross-section, or of circular section suitably grooved, to enable it to be fixed mechanically to the supporting ears.

The following table gives particulars of these wires:—

TABLE 193.—*Constants of Copper Trolley Wires.*

Size of Wire.		Sectional Area. Sq. In.	Breaking Load. Lb.	Resistance.	Weight.
S.W.G.	Diam. Ins.			Ohms per 100 yds.	Lb. per 100 yds.
4/0	0.400	0.126	6 280	0.019 5	146
3/0	0.372	0.109	5 240	0.022 6	126
2/0	0.348	0.095	4 750	0.025 8	110

The ultimate tensile strength is from 23 to 25 tons per sq. in.; the elastic limit from $7\frac{1}{2}$ to $12\frac{1}{2}$ tons per sq. in.; Young's modulus of elasticity 18×10^6 lb. per sq. in.; specific resistance $0.69 \times 10^6 \Omega$

per in. cube. In Specification No. 23 (1933) the B.S.I. recommend that the minimum tensile breaking strengths, in tons per sq. in., for British Standard Trolley Wire, shall be: for copper, 2/0 S.W.G., 24 tons round, 23 tons grooved; 4/0 S.W.G., 23·5 tons round, 22·5 tons grooved.

Silico-bronze has a resistance about 2·2 times that of hard-drawn copper, and may require an additional copper conductor in parallel with it, but not subject to wear; its ultimate tensile strength is 31 to 35 tons per sq. in.

A slight addition of cadmium to pure copper has a remarkable effect on its mechanical properties, while (unlike other 'impurities') affecting its conductivity but slightly.* The tensile strength and resistance to bending, torsion and high temperatures are greatly increased. In a test of a trolley wire under working conditions the loss in diameter during eight months was less than one-third as much for copper-cadmium as for pure copper. It must be remembered, however, that wear is due generally far more to arcing from vibration than to mechanical friction from the collector.

In the 'Memorandum Regarding Details of Construction of New Lines and Equipment' issued by the Minister of Transport (1926), which applies also to reconstructed lines, the following requirements as to the overhead equipment—of the nature of Regulations, though not so named—occur under the heading: I. Constructional Details:—

B. OVERHEAD ELECTRICAL EQUIPMENT.

(1) The electrical pressure or difference of potential between the overhead conductors used in connection with the working of the tramways and the earth, or between any two such conductors, shall in no case exceed 600 V. The electrical energy supplied through feeders shall not be generated at or transformed to a pressure higher than 650 V, except with the written consent of the Minister of Transport, and subject to such regulations and conditions as he may prescribe.

(2) Centre posts must not be used without the consent, in every case, of the Minister of Transport.

(3) The stone-kerbing round isolated centre or span-wire posts should not be such as to enable any person to stand upon it as a refuge, unless the clearance is ample for safety.

(4) Span-wire construction is preferred, so as to provide for trolley wires being centrally spaced over their respective tracks. Bracket arms, not as a rule exceeding 16 ft. in length, may, however, be used if this form of construction is economically desirable.

* *Electrical Review*, Dec. 7, 14, 1928.

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(5) The interval between the supports to which the overhead conductors used in connection with the working of the tramways are attached shall not, except with the approval of the Minister of Transport, exceed 120 ft., and as a general rule the overhead conductors shall in no part be at a less height than 20 ft. from the surface of the street, except where they pass under bridges.

(6) Each positive conductor shall be divided up into sections not exceeding (except with the special approval of the Minister of Transport) one-half of a mile in length, between every two of which shall be inserted an emergency switch so enclosed as to be inaccessible to pedestrians.

(7) No gas or electric lamp bracket shall be attached to any pole unless either triple insulation is provided between the pole and the overhead conductors or the pole is bonded to the tramway rails.

In the case of any lamp suspended from the span wire carrying the overhead tramway conductors, that portion of the span wire from which the lamp is suspended shall be separated from that portion or portions on which the trolley wire or wires are carried by a suitable insulator.

NOTE.—Guard Wire Regulations are dealt with in a separate Memorandum entitled 'Guard Wires on Electric Tramways and Light Railways Laid on Public Roads.'

The trolley wire may be carried in several ways: *centre-pole construction*, where the poles are erected between the lines of a double track, with brackets on either side carrying the trolley wires more or less over each track; *side-pole construction*, with long brackets projecting out over the single or double track, as the case may be; the same with shorter brackets and a side-running swivelling trolley; and *span-wire construction*, where the trolley-wire is hung from a network of steel bearer wires carried on poles out of the way of the traffic. In broad thoroughfares, with the lines in the middle, the first method is perhaps most generally adopted, as by marking the centre of the road it assists in regulating the traffic, and the poles can be used to carry arc lamps or clusters of glow lamps. In narrow streets and in busy streets of medium width, centre poles constitute a dangerous obstruction, so it is desirable to use either side poles and long brackets when the track is near the edge of the road, or the span-wire method of support when the track is in the centre. At crossings and curves and in large open spaces the last method is the most usual.

With such moderate speeds as are customary on tramways, the considerable sag in the trolley-wire spans—usually of 120 ft.—is unimportant. For high-speed work, catenary suspension (§ 914, railways) is used.

Guarding the Trolley Wires.—Guard wires, to protect other overhead lines—especially telegraph and telephone lines—are a

necessary evil in Great Britain; though whether they do more harm than good is a moot point. A Ministry of Transport paper * lays down a Regulation on the subject, accompanied by an Explanatory Memorandum with six diagrams showing how the guard wires are to be arranged. For this, the original must be consulted; but the Regulation is as follows:—

Regulation. If and whenever telegraph, telephone or other wires, unprotected with a permanent insulating covering, cross above, or are liable to fall upon, or to be blown on to, the overhead conductors of the tramways (or railways), efficient guard wires shall be erected and maintained at all such places:

Provided that this Regulation shall not apply to Post Office over-road stay wires where they are earthed at each end to the tramway (or railway) rails.

910. Poles and Brackets (Tramways).—Tramway poles are almost always steel, of graduated tubular form, and of very stout construction, owing to the severe side strains to which most of them are exposed. The British Standards Institution classes tramway poles as Light, Medium, Heavy and Extra Heavy, and specifies † that—

2. The poles may be made of three separate sections (sectional poles) swaged together when hot, so as to make a perfect joint; or they may be made in one piece with two reduced parallel steps (stepped poles). Poles of both types shall be made either by the hot-rolled weldless process or the lap-welded process, of steel of a tensile strength of not less than 24 nor more than 42 tons per sq. in. The lap-welded seams in the sections shall be set at an angle of 120° to each other.

The standard overall length of poles of all classes is 31 ft., divided into top 7 ft., middle 7 ft. and bottom 17 ft. (or bottom 19 ft., making 33 ft. overall, for medium, heavy, and extra-heavy classes only).

The prescribed outside diameters are shown in Table 194.

The minimum thickness allowed is also laid down, *viz.* from $\frac{9}{32}$ to $\frac{9}{16}$ in. The prescribed tests (for 5 % of a consignment) are a 6-ft. drop-test for joints and a bending test. In the latter the pole is rigidly supported for 6 ft. from the butt and loaded, as a canti-

* * Guard Wires on Electric Tramways and Light Railways Laid on Public Roads,' Ministry of Transport, 1921.

† B.S.I., 'British Standard Specification for Tubular Traction Poles,' No. 8 (1931).

TABLE 194.—*Dimensions of Standard Tramway Poles.*

	Top.	Middle.	Bottom.
Light	5½ ins.	6½ ins.	7½ ins.
Medium	6½ „	7½ „	8½ „
Heavy or Extra Heavy . .	7½ „	8½ „	9½ „

NOTE.—These figures relate to 31 ft. poles. For 33 ft. poles the only differences are that the outside diameters for Extra Heavy poles are 8½, 9½ and 10½ ins. at top, middle and bottom.

lever, 18 ins. from the top, the load being applied at right angles to the axis of the pole, which is fixed horizontally. Upon the application of the following loads the temporary deflection and permanent set, measured at the point of application, must not exceed the following values:—

TABLE 195.—*Test Loads on Standard Tramway Poles.*

Type.	Load for Temporary Deflection not Exceeding 6 ins. Lb.	Load for Permanent Set not Exceeding ½ in. Lb.
Light poles	750	1 000
Medium poles	1 250	1 750
Heavy poles	2 000	2 500
Extra Heavy	2 750	3 250

The weight of the above poles in lb. is approximately as follows:—

	Light.		Medium.		Heavy.		Extra Heavy.	
	ft.	33 ft.	31 ft.	33 ft.	31 ft.	33 ft.	31 ft.	33 ft.
Sectional poles	700		872	1 079	1 130	1 394	1 437	1 607
Stepped poles	674		851	1 144	1 132	1 473	1 538	1 648

For ordinary *centre-pole construction*, on straight runs, the pole can be comparatively light and erected vertically. In *span-wire* or *side-bracket* work and on all curves it is necessary to give the poles a rake in the direction to oppose the pull on them, whether due to dead-weight, as in the case of very long projecting side-brackets, or to strain, as in the case of span-wires and curves. With span-wires and curves convex to the poles the strain is an

inward pull, while on curves concave to the poles the dead-weight and strain oppose one another, and the strain is the factor which must be reckoned with as the more powerful. Where span-wires are used the strain is very great if the spans are large and the wires strained up tight, and a rake up to one foot is sometimes necessary.

The height of poles is regulated to ensure a minimum height for the trolley wire, in the centre of spans, of 20 ft., as prescribed by Regulation 5 (§ 909), unless lighting is to be done on the same poles (as is sometimes the case), in which event the height is increased accordingly. Spans may not exceed 120 ft. under the same regulation, and the trolley wire is generally strained up to give a maximum dip of about 15 ins. in hot weather on the full span. On curves the spans are shortened, since the poles cannot easily be stayed laterally, as other overhead lines can, and the dip is proportionately reduced. One rule is to allow a dip of $\frac{3}{4}\%$ of span at the average temperature. Poles are set in concrete or in rammed earth and stones according to the nature of the ground, in holes from 4 to 6 ft. deep, the base generally resting on a block of stone.

Brackets are made of pipe and, where a bracket projects over 6 ft., it is generally necessary to put in a stay rod from the top of the pole; in the very long brackets used for side-pole construction on a double track several stays are required, running out to different points along the bracket. In many cases the trolley wire is not supported by the bracket itself, but by a steel wire stretched between the pole and the end of the bracket. Such a method of 'flexible suspension' does away with the jar as the trolley wheel passes the poles, which at high speed is an important matter.

In *span-wire* work stranded mild steel bearer wires are employed, hung from poles on both sides of the street. The determination of the correct amount of dip to allow on span-wires is a somewhat complicated matter, especially on curves; but the main point is that the height of the trolley wire in the middle of a span must not be less than 20 ft. at any time. The more extreme the cold and hot weather temperatures, the more carefully do the details require to be worked out to avoid, on the one hand, excessive dip, and, on the other hand, excessive strain.

911. Suspension and Insulation of Trolley Wire (Tramways).—The wire has to be held in position over or near the

tracks, and insulated from its supports, while at the same time the arrangements for holding it must allow the trolley wheel or collecting bow to run freely past. The wire is therefore soldered to or clamped in grooved ears of gun-metal, shaped to fit the top of the wire accurately. The ears are held from above by special insulators which in their turn are fixed to the brackets or suspending wires; but in the case of bracket construction the system is somewhat rigid and apt to cause breakage, so the practice is often to suspend the ear flexibly, as mentioned above. If the collector is momentarily jolted off the wire the circuit is opened, and arcing occurs; this wears away the wire and also destroys its temper.

Special types of mechanically protected insulators have been developed as the result of experience in traction work, built up of compressed insulating material partially encased in a metal jacket, but with improvements in porcelain manufacture the latter has come back into use.* On curves two insulators are placed side by side and bridged across by a metal bar which carries the ear. Special types of ear are used for splicing the wire at a joint and for taking feeder connections. Anchor wires are attached to special ears where the strain is abnormal, and also at regular intervals to hold up the line generally, in case of a break at one point. Special 'section insulators' are used for isolating the $\frac{1}{2}$ -mile sections into which the line must be divided [Regulation 6, § 909], and at these points the trolley wire is connected to the section pillar containing switchgear, etc. Special frogs (points) and crossing fittings are also required in the trolley-wire circuit.

912. The Overhead System on Tramways; Collection of Current.—In Great Britain, the apparatus mounted on the car roof, for collecting current from the line and conveying it into the car, generally consists of a 'trolley wheel' carried by a long arm or 'trolley pole,' with a powerful spring pressing the wheel up against the trolley-wire; or, alternatively, of a sliding metal 'bow,' rubbing on a zig-zag or staggered contact wire, similarly actuated by springs. The trolley, either under-running or side-running, is generally used in British tramway practice; the

* Among the Regulations issued by the Minister of Transport in the 'Statutory Rules and Orders' relating to particular undertakings is one, No. XII., prescribing that 'Each separate insulator . . . shall be tested not less frequently than once a

sliding bow (§ 913) is usual on the Continent, and is coming into favour in this country.

Trolleys may be either *under-running* or *side-running*, according to the position of the trolley wire in relation to the track; and various diameters, weights and shapes of groove are to be found. One and all of these are liable occasionally to jump off the line, especially at junctions and crossing places; and accidents have been caused by the trolley wire being fouled and broken. The trolley pole is made to swivel, both for adjusting itself to inequalities in the line and to enable it to be reversed at terminal points. It is of course essential, with any method of collection, that the wear should fall on the collector rather than on the conductor; the wear on the latter is reckoned at about 1 % per annum, but depends on the wire used (§ 909).

In their Report No. 23 (1933) the B.S.I. lay down, for guidance rather than as a compulsory standard, the dimensions of a British Standard Trolley Wheel Groove:—

Width outside	= $1\frac{3}{8}$ in.
Depth	= $\frac{3}{4}$ in.
Radius at the bottom of the V	= $\frac{3}{32}$ in.
Angle of V-groove	= 65°

Safety precautions are laid down by the Minister of Transport, in the Memorandum already referred to, regarding the circuits in connection with the line current:—

II. CAR EQUIPMENT.

(8) All railings shall be connected with earth, except that those used by passengers in mounting or alighting from a carriage may be insulated if so desired.

(9) All electrical conductors fixed upon the carriages in connection with the trolley wheel shall be formed of flexible cables protected by india-rubber insulation of the highest quality, and additionally protected wherever they are adjacent to any metal so as to avoid risk of the metal becoming charged.

(10) The trolley standard of every double-deck carriage shall be electrically connected to the wheels of the carriage in such manner as either to prevent the possibility of the standard becoming electrically charged from any defect in the conductors contained within it, or in the event of the standard becoming electrically charged to give a distinctive and continuous warning signal, recognisable both by day and by night to the driver or conductor.

NOTE.—This requirement will not apply to the trolley base on the top cover of double-deck cars.

(11) An emergency cut-off switch shall be provided and fixed so as to be conveniently reached by the driver in case of any failure of action of the controller switch.

EQUIPMENT: THE OVERHEAD SYSTEM ON RAILWAYS.

913. The Overhead System on Railways; Collection of Current.—Where the pressure exceeds 1 200 V on the line, the third-rail system (§ 920) is not allowed in this country, and overhead construction must be used. Much of what appears in the preceding paragraph relating to this system on tramways obviously applies to the same system on railways; but in the latter case: (a) higher pressures are generally used now, and still higher will be used in the near future; (b) even with these higher pressures, much greater currents have to be collected; (c) collection takes place at far higher speed; and (d) for the time being, the overhead construction is subjected to the smoke and dirt of steam locomotives. Examples and details of overhead construction are given in the following paragraphs; but, as the method of construction is dependent on the method of collecting the current, this latter is dealt with first.

Although the employment of trolley-wheel collectors is excellent in its proper sphere, it is unlikely that they will be used to any great extent on future railway work proper, as distinct from magnified tramways; but they are still used to a large extent on inter-urban lines in the U.S.A., even for such high speeds as 50 m.p.h. Thus trolley wheels 10 ins. in diameter were adopted to collect current from overhead lines on the Oakland, Antioch, and Eastern Rly. These wheels weigh about $10\frac{1}{2}$ lb. each, and it is found that they keep smooth and do not give trouble by heavy arcing and jumping off the line, as was the case with smaller wheels originally in use. One wheel is found to carry 450 A for $1\frac{1}{2}$ hrs., 900 A for $\frac{1}{2}$ hr., or 1 200 A momentarily without appreciable heating, so that a single collector suffices for a train of four or five coaches.

At the present day, however, the bow or pantograph collector is used almost exclusively for railway work with overhead construction, since it cannot in any circumstances jump off the line or foul at frogs or crossings. By having more than one collector very heavy currents can be negotiated, and arcing due to vibration or passing on to a new section can be virtually eliminated.

The bow collector itself—so called because it is shaped like a strung bow, convex side upwards—consists of a framework, usually of bronze, with a sliding contact surface consisting either

of a strip of aluminium or a 'pan' of steel about 6 ins. wide. The contact piece is made of sufficient length to distribute the wear, which is often taken on longitudinal copper strips instead of on the pan. In place of the rubbing contact so obtained, a rolling contact piece is often employed, for which purpose a steel tube of the necessary length, mounted on roller bearings, is used. Both types require grease lubrication in plenty. The sliding contact has a normal capacity of about 150 A and a life of 5 000 miles, as against about 500 A and 15 000 miles for the roller. Far higher currents than these may, however, have to be collected. The special trolley wheels used on American inter-urban lines will collect from 800 A during acceleration down to 300 to 500 at running speeds. With a single pantograph collector it is recorded* that up to 5 000 A was collected sparklessly at 60 m.p.h. at the Erie works of the General Electric Co. This is equivalent to 7 500 kW at 1 500 V or 15 000 kW at 3 000 V, which is far beyond the requirements of any single present-day locomotive, even in America; where the heaviest service yet planned would require two locos of 5 000 kW each for a 6 000-ton train ascending a 2·2 % grade, on the Virginian Railway. These results are attributed to improvements in the flexible type of overhead construction adopted, consisting of loop hangers with a twin grooved copper trolley wire, supported from alternate points of a secondary messenger cable of steel (Fig. 402, facing p. 614).

While a light spring-borne frame, comparable to a trolley pole, is sometimes used for light work, the ordinary method of support for the bow is by a more complicated pantograph construction. The upward pressure on to the trolley wire is obtained pneumatically, in opposition to a downward spring pressure which acts in case of air failure. The pantograph frame gives great lateral stability, which is entirely (and inherently) absent in a trolley pole. The considerable length of wearing surface on the collector, at right angles to the track, ensures a reasonable life and absence of grooving, which would rapidly cut it right through if the contact wire was not staggered (§ 912).

914. The Overhead System on Railways; Line Construction.—Even the lightest pantograph structure, coupled with the weight of the actual collector, gives the whole apparatus such

* *General Electric Review* (N.Y.), Vol. 18, p. 619.

considerable inertia that the contact wire cannot be allowed to sag as on a tramway, or there would be constant makes and breaks and arcing. In any case, where a large amount of power has to be collected at high speed, and perhaps at high pressure also, as in the case of electric railways, any appreciable dip on the contact-wire is objectionable; it is therefore the practice to run 'messenger' wires, and to suspend the line conductor from them by frequent hangers of such lengths as to ensure its being practically horizontal throughout (*see* Fig. 405, § 915). There are several varieties of this 'catenary construction.' The simplest consists of a single bearer or messenger wire vertically over the conductor; a better mechanical construction is obtained by two such wires in the same horizontal plane, with the conductor forming an equilateral triangle below them; another method is to attach the contact-wire to a horizontal wire, itself suspended from a catenary. With all such arrangements there are difficulties due to changes of temperature affecting steel and copper wires differently, and various devices for keeping the conductor under constant tension have been used.

The Advisory Committee of the Ministry of Transport, in its Final Report, recommended the following clearances:—

The standard clearances, after allowance has been made for curvature and super-elevation, including any movements of the live wire or conductors and lateral movements of the collectors, under any circumstances likely to arise, shall be:

- (a) Between the underside of any overhead live wire or conductor and the maximum load gauge likely to be used on the line:
 - (1) In the open, 3 ft.
 - (2) Through tunnels and under bridges, 10 ins.
- (b) Between any part of the structures and the nearest point of any live overhead wire or conductor, 6 ins.
- (c) Between rail level and overhead conductors:—
 - (1) At accommodation and public road level-crossings, 13 ft.
 - (2) At places where there is a likelihood of men in the conduct of their duties having to stand on the top of engines or vehicles, 20 ft.
- (d) Between any part of the collector gear and any structure, 3 ins.

The contact wire, as on tramways, is grooved to enable it to be gripped mechanically. It may be of hard-drawn copper, silico-bronze or cadmium-copper (for the properties of which see paragraph 909 above), and galvanised steel has also been used (on the Lake Erie and Northern Railway, Canada),* see paragraph 917.

The hangers or droppers are placed sufficiently close together—10 or 15 ft.—to ensure keeping the contact wire practically level;

* *The Railway Engineer*, June, 1923, p. 227.

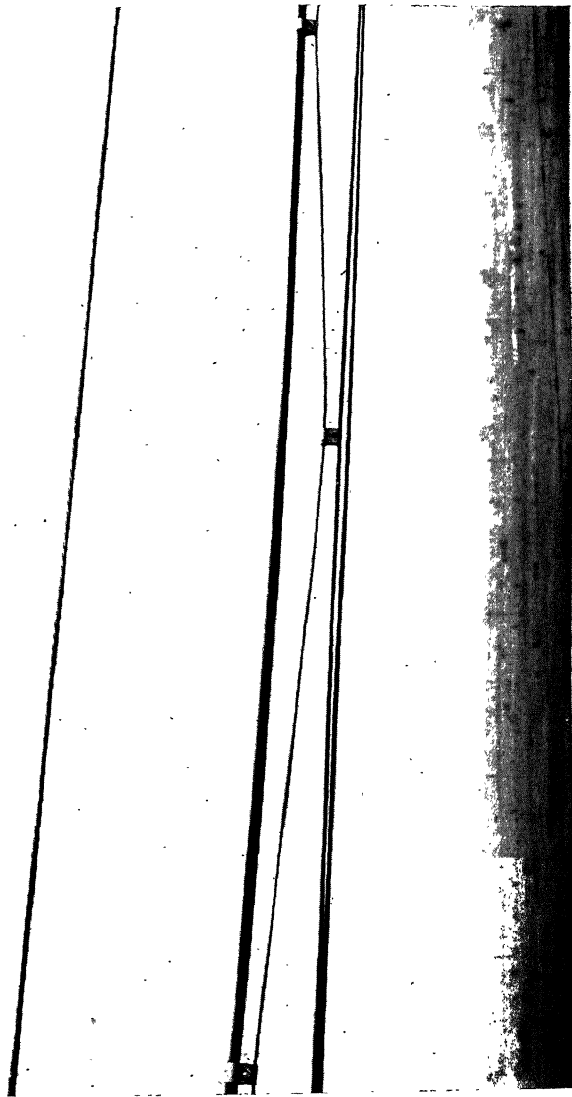


FIG. 402.—Laced type construction of double wire overhead system, showing method of supporting trolley wire.

[To face page 614.]

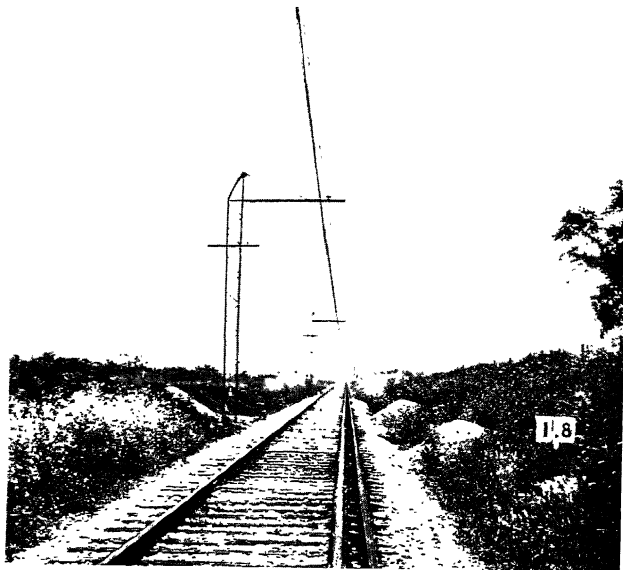


FIG. 403.—Overhead trolley suspended from latticed side-bracket poles.

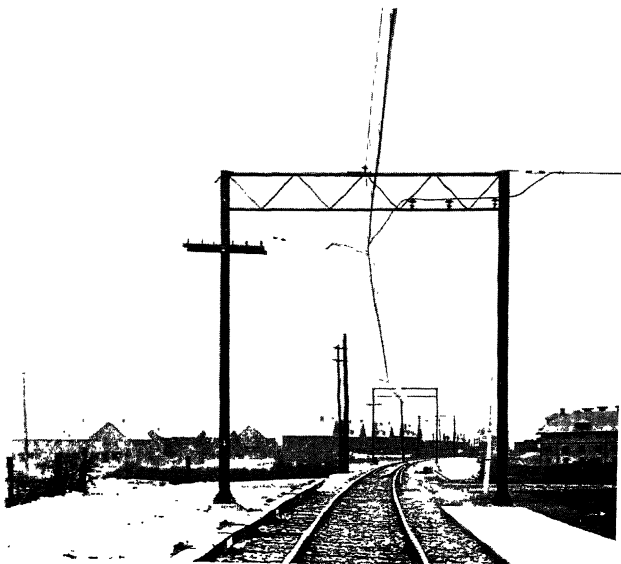


FIG. 404.—Overhead girder suspension on a curve.

[To face page 615.]

and they are flexible enough to allow the requisite vertical movement of the contact wire as the collector passes under the points of support. The catenary wire may sag up to 2 or 3 % of the span: it is suspended between bracket arms, gantries or girders from 100 to 200 ft. apart, and insulated from them but not from the contact wire. Where the current is very large, the messenger wire may also be of copper, in parallel with the other. Where the number of parallel tracks to be dealt with would involve very long cross-girder supports, the 'cross-catenary' system may be used, in which the messenger wires are hung from transverse span-wires supported, with considerable sag, between towers at the side of the track. The double sag involves higher towers as a set-off against the absence of a girder structure, but gantries are required for anchoring the overhead wires at intervals, so as to localise the effects of a break and prevent any appreciable sag in the contact wire. To obviate the swaying of the contact wire, the messenger wire is held by horizontal steadying wires at intervals. On curves, owing to the super-elevation, the collector will be tilted towards the inside, and the contact wire must be located accordingly. It is invariably staggered alternatively on either side of the centre line, so as to ensure even wear on the collector and absence of grooving—which, however, cannot be altogether avoided; about 18 in. total play is generally allowed. (This applies equally to tramways employing this system.) The insulators are of porcelain, the suspension type being generally used for high pressures, with several units connected in series at each point of support. Figs. 403 and 404 * illustrate light bracket arm and light girder construction respectively, and Fig. 405 shows heavier girder work.

Special construction has to be adopted in tunnels and under low bridges, where the headway is reduced; it may even be necessary to lower the roadway foundation level. Under a bridge a dummy section can be used, to keep the bow out of trouble, but this is inadmissible over any appreciable length as it might result in stalling a train. With high speeds, the contact wire must be brought very gradually down from its normal level to any required lower level, about 1 % being the highest gradient for pantograph collection.

* These illustrations, and also Fig. 402, are from photographs kindly supplied by the *General Electric Review*, Schenectady, N.Y.

§ 915 ELECTRICAL ENGINEERING PRACTICE

In connection with the overhead construction, reference has already been made in § 372 (3), Vol. 1 (5th edition), to the use of high-speed circuit-breakers for sectionalising the line in localities subject to severe lightning storms. This application was developed on the Natal Railways, after lightning arrestors had been found incapable of dealing with the situation in time to prevent the follow-through power arc burning out the insulator clamps.*

SOME EXAMPLES OF ELECTRIC RAILWAYS WITH OVERHEAD CONSTRUCTION.

915. A Suburban Line.—As an interesting example of a D.C. suburban line the Bombay, Baroda, and Central India Railway may be cited. Some 20 route miles, mostly of double track (with a certain amount of 4-track), totalling 57 track miles, have been converted from steam, in order to quicken up the 80 minute journey between the terminus in Bombay and Borivli. Particulars of the power supply for this work were given in paragraph 868, and by the courtesy of the *Electrical Review* and Callender's Cable and Construction Co. the following description and illustration are given.† For a description of the rolling stock, see the *Electrical Review*, Vol. 102, p. 807.

The traction line equipment follows normal practice and consists of an overhead contact wire of 0.25 sq. in. sectional area, supported by droppers at intervals from a stranded copper catenary of 0.375 sq. in., giving an area of 0.625 sq. in. per track; the cable, in turn, is suspended with double insulators from steel structures spaced normally 220 ft. apart, the return circuits being *via* the bonded track rails.

The lattice steel-work was so designed that equipment for all tracks spanned can be supported in the event of remaining lines being electrified at some later date. The catenary is supported at each structure by a two-disc suspension insulator of special design, which, in turn, is bolted to a movable plate attached to the lower boom of the bridge girder by hook bolts; this arrangement enables the overhead wires to be easily moved across the tracks in either direction in the event of a breakdown, thereby leaving room for

* 'The Electrification of the Pietermaritzburg-Glencoe section of the South African Railways,' F. Lydall. *Journal of the I.E.E.*, Vol. 66, p. 1042.

† *El. Rev.*, Feb. 3, 1928.

the operation of a crane. The catenary, when fully loaded with contact wire and droppers, sags 6 ft. at 85° F. with no wind and a span of 220 ft. In each span a 0.15 sq. in. flexible copper bond between the catenary and contact wire prevents current flowing through the droppers, and all fittings in direct contact with live equipment are made of gun-metal containing 80 % copper. The contact wire is 17 ft. 6 ins. above rail level and is staggered 9 ins. alternately to each side of the track at structure positions to prevent concentrated wear of the pantograph.

Every mile of equipment is rigidly anchored, two structures being used for this purpose, and at these points catenary and contact-wire adjusting links are provided; these overlap spans isolate each mile of equipment in the event of mechanical failure, and the system is also sectionalised electrically at certain overlap positions by rapid-action air-break switches mounted on extensions of the steel structures and operated from the ground level by hand. To guard against nesting birds creating short-circuits,* the system has been provided throughout with special insulation, cross-arms and the like being protected by impregnated teak planks supported on porcelain troughs and connections of 'Ancalite' insulated cable.

On single tracks, cantilever structures with extension brackets carry the cross-span construction; on curved track, pull-off masts erected in mid-span positions register the contact wire over the centres of tracks; sidings are equipped with a steel catenary in place of copper, the other equipment being the same as for running tracks. An example of the special means adopted for carrying the overhead equipment beneath low overbridges is the termination of the catenary on each side of the bridge on end-strain insulators and bonding it by means of 0.375 sq. in. 'Ancalite' cable carried underneath; the contact wire is suspended by small single-loop droppers from a 1-in. diameter steel tube running the whole width of the bridge and insulated by means of inverted pedestal insulators

* This is no fanciful danger. The Indian Telegraph Department has in its museum a complete crow's nest, made of cut ends of telegraph wire, and another of spectacle frames—including some gold ones—for the apparent theft of which a shop assistant got into trouble. In both cases these were built on telegraph lines, which were short-circuited. Crows have made similar attempts on overhead power lines and have compelled the railway authorities in Bombay to add bird guards on all their 1 500-V track equipment.

§ 916 ELECTRICAL ENGINEERING PRACTICE

adapted for attachment to steel channels on the under side of the bridge.

Approximately 2 000 tons of steel and 500 tons of copper were used for the overhead equipment alone, and the total tonnage of 22 000-volt underground cable supplied and laid was 720 tons; all wire, with the exception of the steel catenary, which has a breaking stress of 50 tons per sq. in., was hard drawn, having a breaking stress of 24 tons per sq. in. The accompanying illustration shows various types of equipment during erection: it is a view of the Andheri yard, showing under- and over-hung catenaries at the entrance to the 'stabling' sidings, and also 22-kV transmission line.

916. Another Suburban Line.—As a further example of a suburban line, with which also the writer is familiar, the Great Indian Peninsular Railway may be taken, as the main line is now also in process of conversion (§§ 918 and 926). The initial length on Bombay Island was set to work in 1925, and extension of the suburban service to Kalyan Junction is proceeding. The description and illustrations are used by the courtesy of the *Electrical Review** and a description of the locomotives will be found in that paper, Vol. 102, p. 809.

The initial scheme comprises the electrification of the 9-mile harbour branch of the G.I.P.R. from Victoria station terminus to Kurla, just across the causeway that links the two islands of Bombay and Salsette. The present passenger traffic on the harbour branch is very small, as the line is used chiefly for the carriage of goods from up-country to the docks, but the area through which the line runs is being developed by the Bombay Improvement Trust, and with the idea of dealing with the passenger traffic the line has been extended into Victoria terminus by the construction of a viaduct over the main line. The electrification was undertaken not only on account of the saving in working costs thereby obtainable, but because the capital outlay for electrical equipment was found to be considerably less than that needed for steam operation owing to the heavy gradient leading up to the viaduct over the main line.

Energy is purchased from the Tata Co., whose hydro-electric stations (§§ 241, 242) are situated some fifty miles off in the Western

* *EL. Rev.*, Vol. 96, p. 260.

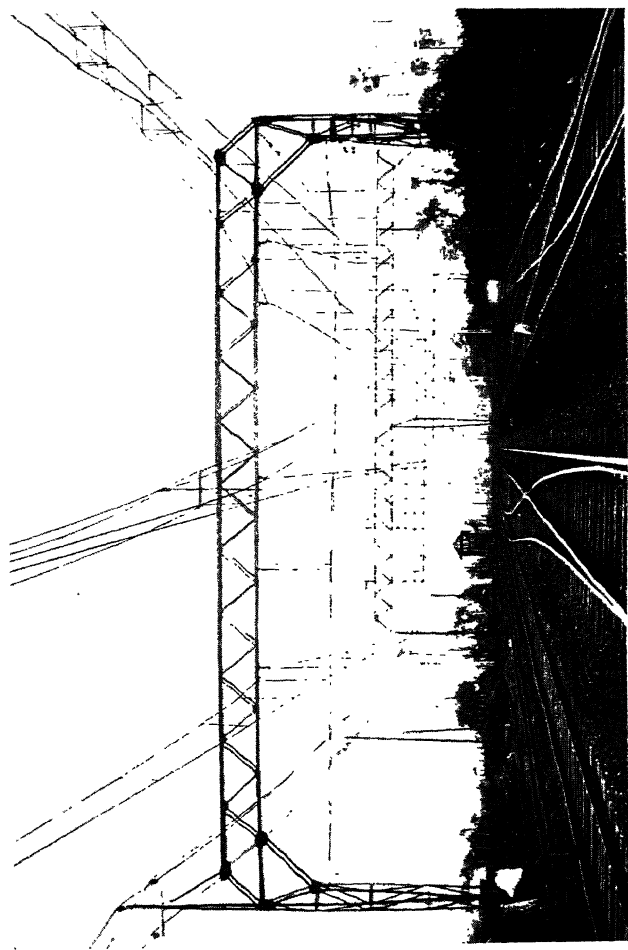


FIG. 405.—Track equipment and 22-kV transmission line on the Bombay Suburban Electrification.
[To face page 618.]

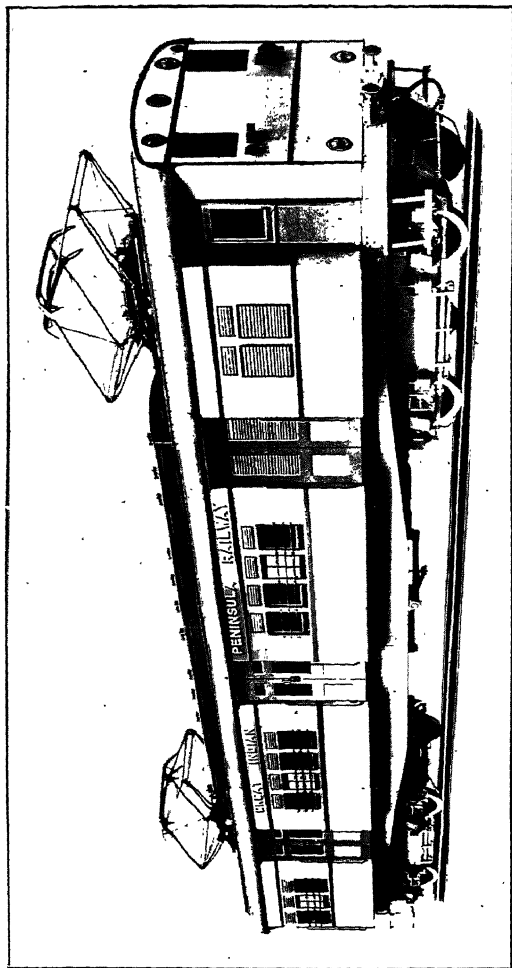


Fig. 406.--All-steel motor coach : Bombay Suburban Service.

[To face page 619.

Ghats, and is transmitted at 100 000 V, 50 cycles, to receiving stations at Dharavi and Kalyan, while a receiving station at Parel is used mainly for supplying cotton mills. The voltage is stepped down to 22 000 V at the receiving stations, and the power is transmitted to the Wadi Bunder and Kurla railway sub-stations from Dharavi by means of 3-core cables, and from Kalyan by overhead lines to Thana and Kalyan. It is also intended to supply power to the workshops at Matunga and Parel. The metering for the Kurla and Wadi Bunder sub-stations will be done at Dharavi, while the supply to the Thana and Kalyan sub-stations will be metered in the stations themselves. In order to obtain the simultaneous maximum demand of all the sub-stations, which is necessary for purposes of payment for power consumed, the meters are of the printometer type, synchronised by clocks.

The 22 000-V cables from Dharavi to Wadi Bunder and Kurla are in duplicate, being paper-insulated, lead-covered, with single-wire armouring and laid direct in the ground.

In the first instance, sub-stations have been provided at Wadi Bunder and at Kurla, each containing two 2 500-kW rotary converters for supplying the harbour branch; for the suburban service on the main line two sets of the same capacity will be installed at the Thana and Kalyan sub-stations, and one additional set will be installed at Wadi Bunder and at Kurla, which arrangement will provide a spare set in each sub-station under normal conditions. Each 2 500-kW set consists of 750-V machines coupled in series, giving 1 500 V D.C., and has been specially designed with high overload capacity for short periods; protection against short circuits is provided by high-speed circuit-breakers.

Auxiliary transformers are provided in the sub-stations stepping down from 22 000 to 2 200 V for supplying the railway stations and yards by means of a 3-phase overhead line carried on the track structures. Both the 22 000- and 2 200-V switchgear is armour-clad, compound-filled, and manually operated, with single bus-bars, while the 1 500-V D.C. switchgear is mounted on a steel framework with stonework partitions.

The new harbour branch rolling stock is of the all-steel type designed by Messrs. Robert White & Partners (Fig. 406). The width of the 68-ft. long coach is 12 ft., being the new standard dimension adopted by the Railway Board, and all internal fittings were made at the railway company's carriage workshops

at Matunga. The eight-coach train has a seating capacity of 874 passengers.

For the main-line suburban service a large number of available passenger coaches of modern design have been equipped for use as trailers, with new motor coaches.

Normally trains of eight coaches will be run consisting of two units, each comprising one motor coach and three trailers. For the present thirteen units have been provided at a cost of £254 000, with which it is proposed to provide a service totalling 350 000 train miles per year. Each motor coach is equipped with four motors of 275 h.p. on the one-hour rating, two of which are connected permanently in series to allow for pairs of motors being controlled on the usual series-parallel system. During the monsoon period the tracks may be flooded to a depth of 2 ft. 6 ins., and consequently the motors had to be so designed as to enable them to run totally enclosed for short periods; the arrangement comprises valves on each end of the motor which can be turned by means of a special spanner. The motors are carried in the ordinary way by suspension bearings on the bogie axle and by a nose supported on springs (Fig. 407).

The control is the all-electric cam-shaft system developed by the English Electric Co. A motor-generator supplies power at 120 V for the control circuits, lighting, and fans. Vacuum brakes are used, and the two pantographs per motor coach are arranged for vacuum operation so as to avoid the necessity of a separate compressor. The sanding gear is of the gravity type, controlled by electrically-operated valves.

Direct current at 1 500 V is collected by the trains from overhead equipment of the single catenary type. On those parts of the route where there are four tracks, and the preliminary electrification requires two tracks only, the steel structures are designed to span all four tracks in order to reduce the additional expenditure required at a later date (*i.e.* for the main-line tracks). Also, it has been found necessary to have special structures with a span of 129 ft. in certain cases where it is impracticable to place intermediate supports between tracks. The normal spacing of the structures throughout is 220 ft., and intermediate pull-offs are used on curves having less than 4 800 ft. radius. Anchor structures approximately half a mile apart are arranged so that the catenary and the contact wire overlap for a length of one span.

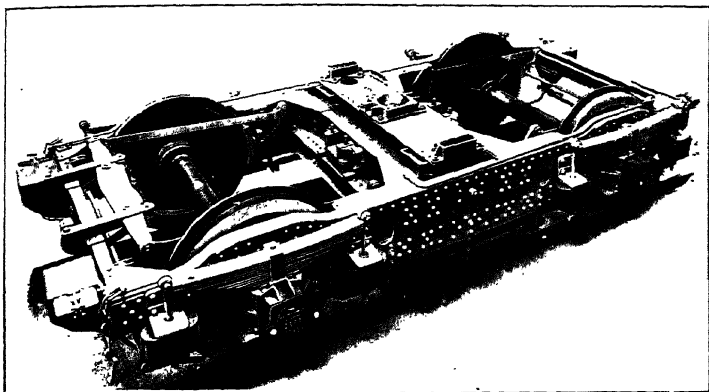


FIG. 407.—Motor bogie : Bombay Suburban Service.

[To face page 620.

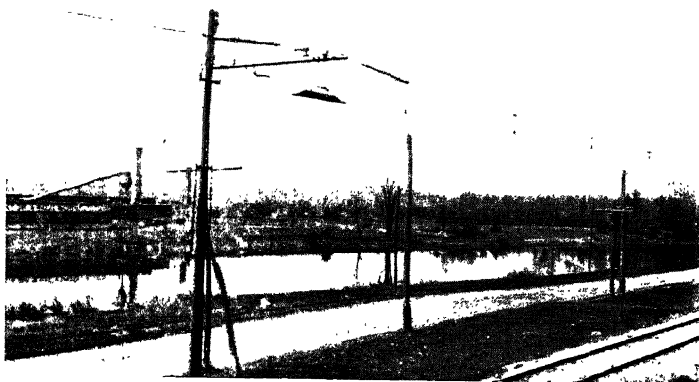


FIG. 408.—Steel-cored aluminium cable for railway catenary and feeders.

The catenary and contact wires are anchored rigidly, no automatic tensioning arrangements being provided, and double insulation is used throughout. The catenary has thirty-seven strands of 0.115 in. diameter copper, and the contact wire is of the grooved type having a section of 0.25 sq. in., giving a total copper section of 0.625 sq. in. per track. The formation of 'hard spots' due to the action of the pantographs is to some extent prevented by the heavy type of contact wire used.

Special cranes were provided, and construction trains, consisting of out-of-date passenger stock, were fitted up in the railway company's workshops for use in the erection of the overhead equipment. Working platforms were built on the tops of the coaches, while the interiors were utilised as foremen's offices and stores.

The return current passes through the running rails, which have two bonds per rail joint of the solid-head type expanded into holes in the web of the rail, installed underneath the fishplates in order to prevent theft. The fishplates are of a special design in order to give the required clearance.

It was found possible to place the contracts for the whole of the plant in Great Britain.

917. Light Overhead Construction with Steel-cored Aluminium Cables.—By way of contrast to the preceding descriptions, Fig. 408 * shows the much lighter pole and overhead work on the Lake Erie and Northern Railway in Ontario; a 1500 V D.C. line, the traffic consisting of an hourly passenger service over fifty miles, together with a heavy freight traffic at night, with trains made up of ten or more thirty-ton freight cars. A novelty is the use of a steel contact wire.

The general nature of the track construction is shown in Fig. 408, the catenary being carried on cantilever brackets mounted on rough-hewn wooden poles. A single catenary is employed, and excessive side swing of the contact wire is prevented by flexible steady braces used at every fourth or fifth pole on tangent track and at all poles on curves, these braces permitting free vertical movement of the contact wire, but preventing horizontal displacement.

While this type of pole construction may not be applicable to

* *The Railway Engineer*, June, 1923: 'A Modern System of Overhead Railway Track Construction.'

the conditions of British railways, the novel features of the contact system itself are worthy of careful consideration, because, not only did the system adopted show marked economies in first cost over other systems considered, but also it promised many advantages in operation which, as far as can be judged from six years' working, have been borne out in practice.

The main difference between the overhead track construction adopted in this case and that in other instances lies in the use for the main catenary of a steel-cored aluminium cable of the type now common for long-distance transmission schemes. The cable consists of sixty-one strands, each 0·1118 in. diameter, the seven innermost wires being of high tensile steel, and the three outer layers (fifty-four wires) being of aluminium.

It should be remarked that the principal advantage of this type over copper for power transmission lines is its substantially lower cost. At the same time, steel-cored aluminium cables are stronger and lighter than copper cables of the same electrical resistance, and the sag under any particular conditions will therefore be smaller. This enables the average span length to be increased, leading to further economies on towers, insulators and erection. In view of these proved characteristics of steel-cored aluminium for power transmission lines, it becomes of importance to examine their possibilities for railway electrification, and the pioneer installation by the Lake Erie and Northern Railway forms the basis for some general conclusions.

The three layers of aluminium wires surrounding the steel core entirely protect the latter from corrosion, while the aluminium wires themselves are as resistant to corrosive influences as are copper wires. It is necessary to lay stress upon this point because, in other applications, the presence of bi-metallic contacts is well known to give rise to the possibility of corrosion. A junction between copper and aluminium, for example, rapidly deteriorates when exposed to moisture, and so does a copper-iron or copper-zinc junction. Between aluminium and iron, however, the electro-chemical potential difference is small, and between aluminium and the zinc coating of the galvanised core of a steel-cored aluminium cable the electro-chemical voltage is smaller still. This, combined with the fact that the close bedding of the aluminium strands round the core, which largely prevents moisture from entering, is the probable explanation of why no trouble has been experienced

with corrosion either during the six years of operation of steel-cored conductors on this railway or during much longer periods of exposure of such conductors on power-transmission lines. Much practical evidence to this effect is extant, and it can be accepted without question that steel-cored aluminium cables have the same very important advantage over plain steel in respect of non-corrodibility as homogeneous non-ferrous catenaries.

Over a copper catenary, on the other hand, a steel-cored aluminium catenary has the advantage of lightness, which often permits the whole of the electrical conductance required to be obtained in a single cable without excessive weight. In this particular instance, the steel-cored aluminium catenary cable has a conductance equivalent to approximately 0.33 sq. in. cross-section of copper, this being amply sufficient to carry the whole of the current. It was therefore unnecessary to provide any great conductance in the contact wire itself, and in this system the contact wire is of galvanised steel, 0.155 sq. in. section. The resistance of this is high in comparison with the steel-cored catenary, so that normally the current carried by the contact wire is extremely small. When the collector of a car passes, current flows from the catenary to the contact wire through flexible bonds, which occur at intervals of 150 ft. The hangers, in between, will certainly act as feeder points to the contact wire, but the amount of current carried by them is indefinite, and it may be assumed that the contact wire is supplied through the definite feeding points, 150 ft. apart. With this assumption, the maximum length of contact wire carrying appreciable current when a car passes will be 150 ft., and, wherever the point of contact with the collector bow, no portion of this 150 ft. of contact wire will carry the full current taken by the car. It will be seen that when the collector bow is midway between the feeding points each of the 75 ft. of contact wire on either side will carry half the current, and that, as the collector passes along, the current in the preceding portions of contact wire will increase and that in the receding portions decrease. Thus, any one point in the contact wire carries current only during the period taken for the collector bow to pass along a distance of 150 ft., which, at 30 miles per hr., is only 3.4 secs., and even during this short period the current rises to a peak and reverses. This explains why, in spite of the comparatively heavy currents per collector, the steel trolley has proved entirely satisfactory.

The advantage of a steel contact wire is that not only is it considerably less costly than copper, but its rate of wear is far smaller, and it has a low coefficient of expansion which is of very considerable importance. It is true that a steel contact wire is subject to a greater rate of corrosion, but no trouble due to this has yet been experienced, and it would appear that the steel contact wire gives promise of longer life than copper under similar circumstances.

In Fig. 409 is shown the method employed for bonding the steel-cored catenary and the contact wire. It will be seen that a short length of flexible copper strand is sweated into an ear on the contact wire, the other end being bolted into a single clamp on to the catenary cable.

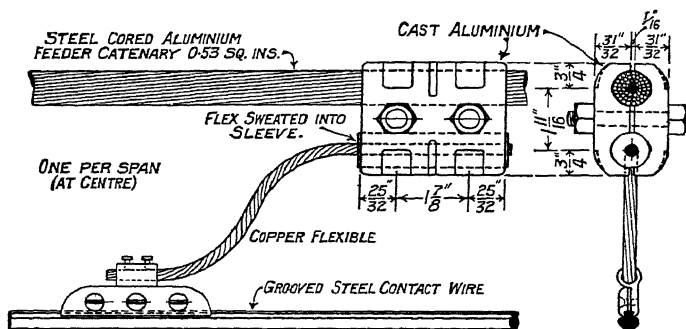


FIG. 409.—Method of bonding contact wire to feeder catenary.

It is well known that, in spite of the vastly different physical properties of the two metals employed in a steel-cored aluminium cable, such a cable, when strung between supports, operates in the same way as would a homogeneous cable having certain values of coefficient of expansion and modulus of elasticity derived from the actual values for the component metals. This is due to the fact that relative movement between the steel and aluminium strands does not take place, owing probably to the very high frictional contact which exists between the strands when the cable is under tension. Thus, a steel-cored aluminium conductor of the type used on the Lake Erie and Northern Railway expands and contracts uniformly with changes of temperature, the coefficient of expansion being 0.000 010 5 per deg. Fahr. The coefficient of expansion of copper is 0.000 009 5 per deg. Fahr., and that of steel 0.000 006 4. In view of these figures, it would appear that the

variations in sag with changes of temperature would be greater with steel-cored aluminium than with either copper or steel, but this is not the case. It must be remembered that any increase in temperature causes a reduction in the tension on the catenary cable, and hence a reduction in the elastic stretch of the cable. An increase in temperature therefore causes (1) a thermal expansion, depending upon the coefficient of expansion, and (2) an elastic contraction, depending upon the reciprocal of the modulus of elasticity. Now, the modulus of elasticity of the composite cable is 13 800 000 lb. per sq. in., while that of steel is 30 000 000, and that of copper 17 500 000 lb. per sq. in. Hence, while the thermal expansion of steel-cored aluminium is larger, the elastic contraction is also larger, and the net result is that the change in sag with a steel-cored aluminium cable is considerably less than with copper and approximately the same as, or a little greater than, that with steel.

On the whole, therefore, besides being considerably cheaper in first cost, the use of a steel-cored aluminium catenary and a steel contact wire would appear to have special mechanical advantages making it very suitable for long span construction, and at the same time the maintenance charges are smaller owing to the elimination of corrosion troubles on the catenary and of rapid wear on the contact wire.

918. Example of D.C. Main Line.—The initial suburban electrification of the Great Indian Peninsular Railway is described in § 916 above. Subsequent stages of development were the electrification of the main line from Bombay to Kalyan Junction (33 miles), this being also part of the suburban system; and thence forking up the Western Ghats to Igatpuri (52 miles) on the Calcutta line and to Poona (85 miles) on another; or 170 route miles in all. The continuous rise from Kalyan to the summit of the Ghats amounts to nearly 2 000 ft. on both branches, and tunnels are plentiful. Until recently it was necessary to employ a reversing station at one point, but by a realignment (before electrification began) this was obviated. Climatic conditions are severe; very heavy continuous rainfall is met with in the higher ground during the monsoon, and a sun temperature of over 160°,*

* The writer has drawn scalding water from his office 'cold' tap at 154° in Calcutta, the pipe from the roof tank running across the flat concrete roof in the full sun.

with frequent thunderstorms. Power is obtained from a steam generating station near Kalyan, without interconnection with the transmission lines of the Tata Co.'s hydro-electric stations close by. The railway is a State line, and through the courtesy of the High Commissioner for India and the India Store Department a brief account of the work follows.

Power is delivered to 11 substations at 50 cycles and from 95 000 to 110 000 V by duplicate overhead lines, each double-circuit (6-wire) from the power-house to Kalyan and single-circuit thence to Poona and Igatpuri—271 miles of circuit in all. Steel-cored aluminium cables, of an ultimate strength of 7 387 lb. and equivalent to 0.1 sq. in. of copper in conductivity, are used, together with a $\frac{7}{12}$ steel earth conductor, the normal spans being 700 ft. The disc suspension insulators are built up to 45 ins. overall length and are supported by cross-arms on steel towers from 63 to 81 ft. high, the factor of safety of nearly every part being 3 under specified conditions* of loading and weather. The minimum clearance allowed between any wire and the ground on this line is 20 ft. on the level at the highest temperature, with a normal height of 23 ft.; and each circuit is transposed once in six miles. Steel-cored aluminium cables are discussed in the preceding paragraph.

There are 11 rotary converter substations and 11 track sectioning cabins above Kalyan. At the substations the 3-phase supply is stepped down and then converted to D.C. at 1 500 V for delivery to the contact wires. In all 26 converter sets of 2 500 kW are installed, each consisting of two identical 750 V machines in series, capable of working regeneratively from the descending freight trains. The converters are started by means of starting motors, semi-automatically, and certain of the substations are arranged for remote control from other stations. Each rotary has its own 3-phase transformer of the outdoor type, oil-immersed and self-cooled, with graded end turns, the whole weighing 50 400 lb. without the oil. Bus-bars for 3 500 A, with isolating devices, high-speed circuit-breakers (0.005 to 0.008 sec.), and instruments are supplied with each converter. There

* Minimum factors of safety and other requirements are prescribed in the Rules under the Indian Electricity Act, *vide The Law Relating to Electrical Energy in India*, fourth edition (Thacker's Press and Directorates Ltd.; Calcutta and London).

are also 42 sets of feeder switchgear and 15 sets of bus-bar sectioning equipment in the various substations; a 110-V battery of 300 Ah capacity at the 10-hr. rate for each, together with a 10 H.P. charging motor-generator; cables, switchgear, an air compressor, lifting tackle and truck, and lightning arresters. In addition, the automatic stations have special gear for performing all operations from start to finish, and the corresponding control apparatus is installed in the others. These operations include closing and opening the 110 000-V circuit-breakers and their isolating and selecting gear and also the control devices for the automatic operation of the converters, etc., with indicators to show that each operation is duly carried out.

The 11 track-sectioning cabins, with 44 equipments, are placed midway between the substations controlling them. Each separate equipment contains an automatic polarised circuit-breaker and accessories for sectioning the track conductor and re-closing an opened section, while indicating the result of each operation at the control point. Each cabin also contains a bus-bar sectioning device, remote controlled.

The line comprises 334 miles of single track, equipped on the overhead system, with rail return. The track structures are ordinarily 220 ft. apart, with pull-off masts where required at curves, and span wire work at rock cuttings, etc. For single lines, cantilever arms are used, and for double and multiple lines girder construction similar to that illustrated in Fig. 405 is used. The control wires are carried on the towers, and in some places the transmission line also. From these structures a main catenary wire is suspended, with a maximum sag of about 7 ft., supporting an auxiliary copper catenary wire, from which the grooved, solid, hard-drawn copper contact wire is hung on droppers; a stagger of 9 ins. each side of the centre being allowed on the straight and 15 ins. on curves. On the main running tracks, using a copper main catenary, the equivalent copper section is 1 sq. in., while on other tracks it is 0.5 and 0.3 with steel main catenary. The contact wire is 0.3 sq. in. throughout. The upper droppers are spaced about 36 ft. apart, and those carrying the contact wire about 18 ft. The normal height of the contact wire is 18 ft. above rail level, reduced to 14 ft. 10 ins. minimum in bridges and tunnels; the maximum height at minimum temperature is 20 ft. 6 ins. The current to be collected at low speeds may be up to 2 000 A and at

top speed 750 A. Double suspension-type insulators are used for supporting the catenary, and the span-wire where used; and diabolo type tension insulators. Paper-insulated, armoured cables connect the line to the substations and track-sectioning cabins. The line is of Indian Standard broad gauge, 5 ft. 6 ins., with a maximum gradient of about 1 in 37 for a considerable stretch up the Ghats. British standard 100 lb. rails are used and also form the return circuit. The locomotives have already been briefly referred to in paragraph 872, but some further technical particulars may be added here.*

For the *passenger locomotives* the leading details are as follows, but the final type has not been selected at the time these sheets are printed off:—

Tractive effort at starting, and up to 36 m.p.h., with full excitation and a pressure of 1 400 V, 24 000 lb.

Ditto at 70 m.p.h., with weak field, 6 300 lb.

Three running speeds, up to 70 m.p.h., but design to be safe up to 85 m.p.h.

Capable of starting a train of 450 tons (exclusive of loco) from rest, on a 1 in. 100 grade on tangent track.

One loco has three twin, or in all six, box-frame motors of 370 B.H.P. (1-hr. rating, B.S.I.) with a continuous rating for the complete outfit, with forced ventilation (4 930 cu. ft. / min.) and maximum excitation of 1 700 B.H.P. without exceeding a rise of 90° C. above an ambient temperature of 40° C. The other trial locos have separate, not twin, motors.

Individual axle drive (quill and flexible) is used, with spur gearing, having a spring-mounted pinion in each gear train.

Electro-pneumatic (50 V) control for series, series-parallel and full parallel grouping, each with and without resistance. Maximum reduction in excitation for speed variation is 35 % by means of tap and shunt.

Air-pressure brakes are fitted on the loco, but vacuum on the train, with the necessary air compressors and exhausters (both in duplicate) on the loco.

Two pantograph collectors, with renewable contact strips to

* See also description and illustrations in the *Metropolitan-Vickers Gazette*, Aug., 1928.

allow for 15-in. stagger of the contact wire on each side of the centre, to collect up to 1 000 A each, operated by air pressure.

Accessories include a 1·8 kW, 50 V motor-generator for control and auxiliaries; blowers for ventilating the motors; and a 24-cell lead battery giving 100 Ah on 10-hr. rating and 100 A for 5 min.

The overall length of these locos varies from 52 ft. 2 ins. to 56 ft. 2½ ins., and the weight is 102½ tons—electrical equipment 87 000 lb. and loco without this 142 000 lb.

The *freight locomotives* are arranged for collective drive with side rods, and on the Ghat section, with continuous heavy gradients, two are mechanically coupled for hauling a train. Regenerative braking is used on the down journey (§ 900). Leading details are as follows:—

Tractive effort at starting and at a speed of 18 m.p.h., with full excitation and a pressure of 1 400 V, 50 000 lb.

Ditto at 28 m.p.h., 17 000 lb.

Three running speeds, up to 35 m.p.h., but design to be safe up to 45 m.p.h.

Capable of exerting continuously any T.E. up to 45 000 lb. at 4 or 5 m.p.h., with 1 400 V on line, without damage to any part.

Capable of starting a train of 500 tons (exclusive of loco) from rest on a 1 in 35 gradient on a straight track, and of attaining a speed of 18 m.p.h. in 3½ mins., under a pressure of 1 400 V; this to be repeated after 5 mins. without overheating the resistances.

Capable of exerting a retarding force of not less than 45 000 lb. by regenerative action alone, at 13 m.p.h., with any line pressure from 1 350 to 1 700 V.

Each loco has four box-frame motors of 650 B.H.P. (1-hour B.S.I. rating), with forced ventilation (3 500 cu. ft. / min.) with the same maximum temperature rise as the passenger locos. The body is mounted on two bogie trucks, each having three driving axles (with 4 ft. wheels) with coupling rods actuated from a jack-shaft by means of a single connecting rod at each side. The gearing includes a flexible helical pinion.

Control and mechanical brakes are as on the passenger locos, but with regenerative braking gear added. Duplicate pantograph collectors are as on passenger locos, and accessories also. The overall length of each loco is 62 ft.; weight without electrical equipment, 155 300 lb.; weight of equipment, 109 000 lb.; total, 118 tons.

919. Alternating Current Railways with Overhead Construction.—Electric railways, both single-phase and polyphase, are becoming so plentiful that description must be confined to brief mention of instances which are out of the common on account of conditions to which steam would hardly be able to stand up. The fuller descriptions of D.C. lines above suffice to show the general trend of modern practice in countries under the British flag.

What is said to be 'The World's Largest Electric Locomotive' * is an A.C. one on the Virginian Railway system (U.S.A.). It is built up in three articulated sections; has an overall length of 152 ft., and weighs 637 tons. The motors aggregate 7 125 B.H.P. and each has mounted at each end of the shaft a pinion which meshes with a flexible gear; the gears are mounted on a jack-shaft, the power being transmitted from the gear centres to the drivers by means of side rods. The loco transformers are designed to take either 11 000 or 22 000 V from the line, and regenerative braking is used.

Single-phase.—The Loetschberg Railway (Switzerland) is a good example of a line dealing with heavy traffic.† The steepest gradient is 1 in 37 and the line rises about 3 000 ft. A steel catenary wire is carried on lattice girders [similar to the construction illustrated in Fig. 405 (§ 915)] and supports a 15 000-V trolley wire of 0.155 sq. in. section. The heaviest locomotives in use are able to travel up the above grade at 31 m.p.h. with a total load of 560 tons. The loco has six driving axles, as well as leading and trailing axles, weighs 142 tons, and is 66 ft. long. There are 12 motors, $16\frac{2}{3}$ cycles, of 375 B.H.P. each, or 4 500 B.H.P. in all, based on 1-hour rating; they are coupled in pairs in series, and are supplied from the line through transformers. The gear ratio is 5.87 to 1, and a new form of quill drive is used.

Three-phase.—Italy has specialised in 3-phase railways, of which a number have been built and supplied from her hydro-electric works, from 1902 onwards. Most of these employ 3-phase energy at 3 000 V, $16\frac{2}{3}$ cycles; but the Rome-Tivoli line is supplied at 10 000 V, 45 cycles. Gearless induction motors are for the most part used, either with plain cascade (2-speed) or with cascade combined with pole-changing (4-speed) arrangement; for goods traffic and the steeper gradients the standard speeds are $15\frac{1}{2}$ and

* *Jour. Amer. I.E.E.*, July, 1925, p. 755.

† *El. Rev.*, Vol. 100, p. 287.

31 m.p.h. and, for express work, 23, 31, 46 and 62 m.p.h. Gradients of $2\frac{1}{2}\%$ are plentiful, and on several lines $3\frac{1}{2}\%$ is found. A double trolley line with plain, not catenary, suspension has hitherto been used, but it is doubtful if this will be retained much longer. Regenerative braking and control is of course used, and was, in fact, the chief reason for adopting 3-phase working.

For heavy service the locomotives * weigh 75 tons (15 tons per axle) and are equipped with two 1 400 B.H.P. asynchronous motors, fed directly from the line at 3 600 V, $16\frac{2}{3}$ cycles. The motors drive the middle axle, which is coupled to the rest by connecting rods. They can operate on 12 or 8 poles and in cascade or parallel, a liquid rheostat being used for starting. Auxiliary plant on the loco is worked from a transformer at 100 V, and includes an electric boiler for the steam heating of the carriages. The highest efficiency of the motors is 97 % and the power factor on parallel working is also 97 %.

Mountain Railways.—Many of the funicular railways, giving access to mountain peaks to those too lazy to climb, are worked electrically, and practically on the counterbalance system, the descending car regenerating most of the power required by the ascending one. The majority of such lines are dependent on tourist traffic entirely. In India, however, there are a number of mountain railways serving the hill stations where 'the notorious people go when it gets too hot for them in the plains,' as the schoolboy happily expressed it. These lines have not only a regular passenger traffic but also, in many cases, considerable freight carriage in such goods as tea and coffee down hill and merchandise for the terminal towns upward. As water power is almost always handy in these localities, these lines are certain to be electrified sooner or later, and the writer (Mr. Meares) reported on several of them. The rise is of the order of 5 000 to 8 000 ft., the gauge from 2 ft. to metre, and the whole track a succession of curves of small radius; in one instance (the Darjeeling Railway) the line makes two complete concentric spirals as it winds up the hill. Of these the Nilgiri Railway (Madras Presidency) offers some special points of interest, and its conversion has been under discussion since 1906. The line is 28 miles long and rises 6 300 ft., mostly in the middle 12 miles up to Coonoor, where the Abt rack is used on the 8 %.

* *El. Rev.*, April 6, 1923.

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gradient. The curves are mostly 328 ft. radius and the gauge is metre. Multiple unit trains were recommended, enabling the steep section to be climbed without the use of the rack, the coefficient of adhesion (§ 890) being $195\,000 / 17\,800 = 11$, as against a safe figure of about 7. Most of the freight up to the hill stations served is still carried by the primitive bullock wagon, owing to the high rates charged by the railway, but it was found that with the traffic then existing there would be a direct saving due to hydro-electric over steam working, amounting to 13 % of the then fuel bill; while with the increased traffic expected by the railway authorities, this would have risen to 56 %.- Water power is found in abundance close to the line, and is now being developed (at the Pykara falls); so the railway will doubtless be electrified at long last.

919A. Kandó System of Single-Phase Traction.—While this book was in the press, work was proceeding on the electrification of the Budapest-Hegyeshalom section of the Hungarian State Railways, using the Kandó system, in which locomotives are driven by polyphase induction motors supplied, through a phase-converter on the locomotive, from a single-phase overhead line at 16 000 V, 50-cycles/sec. This system permits the traction supply to be taken at the industrial frequency from the ordinary transmission network, thus increasing the diversity factor (§ 262, Vol. 1) of the load on the central station, and enabling the traction load to be served by the combustion of low-grade fuel under the most favourable conditions possible in power stations at selected sites, *e.g.* in the mining districts. The principal features of this electrification are as follows* :—

A steam-electric power station of 100 000 H.P. capacity supplies about 100 miles of 110 kV, 3-ph. transmission line with substations for general supply at Budapest and Győr. About 118 miles of railway between Budapest and Hegyeshalom is electrified, with 4 traction substations, 323 miles of trolley wire, and 36 electric locomotives, each of 2 500 H.P. The equipment in each substation includes two 4 000 kVA, 110 / 16 kV single-phase transformers, with the requisite switchgear and auxiliary apparatus. Catenary suspension is used for the overhead contact line.

Taking single-phase supply from the overhead contact line at 16 000 V, 50 cycles, the converter or phase-splitting apparatus supplies polyphase current to the traction motor at 600 to 1 100 V, according to the requirements of load and control. The weight of the phase-converter is relatively small and is compensated by the

* For further particulars see *Railway Engineer*, 1933 (probably August). Later articles will, no doubt, give running experience and results.

advantages gained in other respects. The power factor of the demand from the high-tension line is high and independent of load. In general, the system is flexible and efficient, and regenerative braking is obtained without the use of special auxiliaries.

Single-phase current taken from the overhead line by two collector bows, passes through an oil switch to the primary winding of the phase converter. Polyphase current induced in the secondary winding of the latter is fed to the traction motor. Each locomotive has a single 2 500 H.P. traction motor of the polyphase induction type with two primary windings on the rotor and a single secondary winding on the stator. The connections between the 16 slip-rings can be changed to produce 72, 36, 24 or 18 poles in the rotor, corresponding to synchronous speeds of 83, 166, 250 and 333 r.p.m. on 50-cycle supply. The stator winding is provided with multiple tappings connected to a liquid resistance-starter and controller. Cam-operated contactors control the connections between the secondary of the phase converter and the pole-changing leads on the rotor of the traction motor.

The phase converter is a 4-pole synchronous machine running at 1 500 r.p.m. on 50-cycle supply. This machine is kept running when the locomotive is stationary. The 4-pole armature is fed from a D.C. exciter on the same shaft. There are three distinct windings on the stator, *viz.* :—

(1) The high-tension single-phase winding connected between the collector bows and the earthed return.

(2) An auxiliary single-phase winding in the same slots providing single-phase current at 620 V in antiphase to the main supply. This winding feeds the auxiliary phase of the motor used for starting the converter; also the transformers in the instrument circuits.

(3) A winding with tappings from which 3, 4 or 6-phase current is available for the main traction motors at about 1 000 V.

The stator system of the phase converter is completely immersed in oil, the inside of the oil tank being formed by a bakelite tube in the air-gap. The rotor is water-cooled.

The weight of a 2-8-2 passenger locomotive of the above type is given as approximately 96 tons, of which 53 tons consists of mechanical parts, tools, etc., and 43 tons electrical parts. The adhesive weight is about 69 tons. The contract conditions specify that these locomotives must be capable of hauling a 590-ton train at 62·1 miles (100 km.)/hr. on straight track rising 1 in 1 000; and accelerate to 44·7 miles (72 km.)/hr. in 6 mins. on track of 1 312 ft. radius rising 1 in 149. The 0-12-0 locomotive of the same type is capable of hauling a 1 378-ton goods train at 32 m.p.h. on straight track rising 1 in 1 000.

The consumption of electrical energy, by an experimental locomotive operating on this system, was 26·2 to 27·8 Wh/ton-mile in goods service, and 36·0 to 39·2 Wh/ton-mile in express service.

The cost of the Budapest-Hegyeshalom electrification (at 20 : £1) was given as :—

Electrical equipment (substations, overhead lines, locomotives)	£1 826 800
Telephone, telegraph and signalling circuits.	305 800
Repair shops and running sheds	110 000
Subsidiary work and contingencies	197 400
	<hr/>
	£2 440 000

The capital charges will be about balanced by the reduction in operating costs. As traffic increases, there may be a substantial net saving, compared with steam working, but the primary factor in this case is considered to be the correlated development of national electricity supply based on the utilisation of low-grade fuels (lignite and shale), which could not be burnt satisfactorily in steam locomotives.

EQUIPMENT: THE THIRD-RAIL SYSTEM ON RAILWAYS.

920. Conductor Rails and Collectors ; Railways.—It is not necessary any longer to deal with surface and under-surface systems for tramways—mentioned in paragraph 864 above—as they are obsolete. For railways working at reasonable pressures (up to 1 200 V in Great Britain, at present), the surface system may be and generally is used. In this system a ‘third rail,’ placed either between the two running rails or at one side, is used as the ‘line’ instead of a trolley wire. Where the pressure is only 500 V the current, with heavy trains and high speeds, would be beyond the capacity of an ordinary trolley wheel. The conductor rail is made of low-carbon steel and of large cross-section, which is cheaper than copper and also saves copper in line feeders. The specific resistance of this is about $4.5 \times 10^{-6} \Omega$ per inch cube, or $6\frac{1}{2}$ times that of copper; or, in the standard form, 0.000 016 5 Ω per yd. of 100 lb. rail. A line of 100 lb. rails, of 9.8 sq. in. cross-section, has a resistance per mile of about 0.03 Ω , after allowing 2 % extra for the bonded joints (*cf.* §§ 901, 902, and 903). The ‘British Standard Method of Specifying the Resistance of Steel Conductor Rails’ is laid down in B.S.I. Report No. 68 (1914). The method of comparison with copper just given is useful, but gives rise to misconception as between mass resistivity and volume resistivity. As rails are bought by weight and classified by the number of lb. per yd., the resistance is to be specified in microhms, at a temperature of 15.6° C., of a 100 lb. rail one yard long. If this is R,

microhms, then that of a rail of the same material weighing W lb. per yd. will be $100 R_s / W$ microhms.

The Advisory Committee of the Ministry of Transport, as regards the position of the third rail, desire to recommend that in respect to new electrically operated lines and extensions to existing lines the following regulations should be issued for securing the interchangeability of running:—

- (i) The contact surface shall be in the horizontal plane.
- (ii) The gauge measured between the centre of the horizontal contact surface of contact rails and the gauge line of the nearest rail of the corresponding track shall be 1 ft. 4 ins.
- (iii) The vertical height of the contact surfaces above the plane of the top table of the running rails shall be—
 - (a) for top-contact rails, 3 ins.
 - (b) for under-contact rails, $1\frac{1}{2}$ ins.
- (iv) The vertical height of the contact rail (including, where required, the protection over the top of the rail) above the plane of the top table of the running rails shall be such as to provide the necessary clearance from the load gauges from time to time in use.
- (v) The under-contact rail, where employed, shall provide for the engagement of the contact shoe being made from the side nearest to the running rails.
- (vi) Above the level of the under-contact surface (iii) (b) no part of the contact rail construction shall be at a less distance than 1 ft. $1\frac{1}{2}$ ins. from the gauge line of the nearest track rail, and below the level of the under-contact surface (iii) (b) at a less distance than 1 ft. $7\frac{1}{2}$ ins. from the gauge line of the nearest track rail.
- (vii) The vertical distance between the under side of any contact shoe in the free position and the plane of the top table of the running rails shall not be less than $1\frac{1}{2}$ ins.

The rail is supported on porcelain insulators fixed on the sleepers. In America, for protection from ice and snow mainly, an *under-contact rail* (of ordinary running rail section) is often suspended from a substantial bent-over bracket, with a special insulator held in jaws from the overhung limb. In this country, contact is made either at the side or on the top, the latter method being most likely to find final acceptance as the standard. It is used on the London 'tubes' (600 V) and on the Southern Railway suburban lines. In this *top-contact system* the insulators are about 10 ft. apart, and in stations or places where the bare rail (again of ordinary running rail section) is considered dangerous, side protecting boards are fixed. The collector is usually a cast steel shoe, held by link-work from an insulated support below the locomotive frame, and resting on the rail by gravity alone.

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In the *side-contact system*, as used on the 1 200-V D.C. electrified section of the former Lancashire and Yorkshire Railway, Manchester-Bury route, use is made of a special channel-section conductor rail carried upon insulators fitted with lugs to prevent lateral movement. The rail is practically surrounded by a casing of jarrah wood (which is fire-resisting), except for a slot admitting the current-collecting shoe. The latter is held in contact with the side of the conductor rail head by a spring-loaded mechanism which permits considerable vertical movement of the contact shoe without interrupting contact. No nails or bolts are used in the protective casing, suitable provision is made to prevent water collecting in the latter, and the whole equipment needs little maintenance. Here the shoe that collects the current is pressed against the contact surface by spring pressure.

EXAMPLES OF ELECTRIC RAILWAYS WITH THIRD-RAIL CONSTRUCTION.

921. Southern Railway : Main and Suburban.—The various electrified lines of the Southern Railway afford a good example of recovering lost traffic, inducing new traffic, and meeting tramway and road competition. Starting originally in 1909 with the single-phase A.C. overhead system on certain suburban lines, the system has later been converted throughout to third-rail construction and 600 V direct current ; and, after the success of the suburban lines became assured, the main line to Brighton was also electrified. The combined main and suburban lines now comprise 359 route-miles with 978 miles of track.

(1) *Suburban Lines.*—With steam trains, the limit of possible traffic from Waterloo station had been reached on account of the bottle-neck on the viaduct just outside the main terminus, and, since electric working started, the capacity of the twelve electrified station tracks (out of twenty-one altogether) has been trebled by reason of the factors already discussed in § 865. In the early years of electric working, between 1915 and 1919, the number of passengers carried on the Western section rose from 25 000 000 to 51 000 000.

Power is delivered at 11 000 V, 25 cycles, to a number of substations along the line by means of paper-insulated, lead-sheathed, armoured 3-core cables, carried on short posts close to the line, each substation having a duplicate supply. By means of 1 500 kW

rotaries the A.C. is converted to D.C. at 660 V for supply to the third-rail.* The contact surface of this is 3 ins. above the track rail level and 16 ins. outside it, from gauge of track rail to centre of conductor rail; and a gravity collector is used. The rail joints are bonded with flat copper wire bonds, protected by fishplates; and cross-bonds of 0.15 sq. in. section are used at intervals between the track rails. The conductor rails have four bonds per joint, totalling 1.6 sq. in. area, fixed underneath the flange.

The train 'units' consist of three coaches, comprising two motor coaches with a trailer between them, from one to three such units being made up into a train; the three-coach unit is used during 'slack' hours, and during 'rush' hours an eight-coach train composed of two such units with a two-coach trailer unit between is employed. The units weigh from 94 to 106 tons unloaded and seat from 190 to 218 passengers—say 100 to 110 tons all told, with luggage; an eight-coach loaded train weighing 306 tons. Four 275 B.H.P. four-pole (and four commutating-pole) series motors, of the box type, are used. Each is totally enclosed, fan-ventilated, and suspended from axle bearings on one side and from a nose on the other side, the nose in turn being supported on the bogie frame through a rubber buffer. Solid gears and pinions are employed.

For a collector rail voltage of 660 V and at the speeds stated the tractive efforts at the wheel rim are as follows:—

M.P.H.	25	30	35	40	45	50	55
T.E. in lbs. per motor	5 100	2 700	1 600	1 100	800	660	480

All-electric control is used, with automatic acceleration and multiple-unit working. The contactors are operated by solenoids energised from the line voltage, and controlled through train lines connected to the master controller in each driver's cabin—only one of which is, of course, in operation at any one time. Protection is provided by the equipment fuse and circuit-breaker, the latter being a solenoid-operated switch with series overload trip, and with separate shunt trip operated by the driver when necessary.

* The following figures are of interest; maximum observed current demanded of an individual substation 14 000 A; maximum observed peak load on one 660 V, 1500 kW rotary, 7 500 A; maximum integrated load over 1 h. on one rotary, 1 700 kWh; greatest mean load on one rotary during all running hours of one day, 1 000 kW.

The reversers are connected in the main motor field circuit, and consist of drum-type switches operated by solenoids acting on a rocker arm on the drum shaft. Automatic acceleration is provided for by means of a combined current and time-controlled relay. This relay operates contacts in the control circuits, and governs the sequence of closing contactors; and it is so designed that the control contacts on the relay never break a circuit, the action of closing the contactors being obtained on making the circuit.* This method avoids any danger of bad contacts through burning. The motor current is handled by solenoid-operated contactor switches, the solenoids being connected to the line through a master controller, and suitable interlock contacts being provided to ensure that they close in proper sequence. There are four operating positions of the handle; the first, or switching position, gives series connection with full resistance; the second brings the automatic relay into operation, and the resistance is cut out step by step up to full series; the third position connects the motors in parallel, with full resistance in, the 'bridge connection' being used for the transition from series to parallel; and the fourth position brings the automatic relay into action again, cutting out the resistance up to full parallel. In the event of the driver removing his hand from the 'dead man's handle' of the master controller, it moves upward, automatically cutting off the control current and applying the emergency brakes through a special valve in the controller, working in conjunction with a relay valve. For coasting purposes and when making ordinary service stops, the driver moves the controller to the off position, but keeps his hand on the handle, thus preventing the operation of the emergency gear. Westinghouse brakes are used, with air cylinders as usual on all coaches, and motor compressors on each motor coach, all operated from the driver's cabin.

Taking the Waterloo-Guildford service as an example of train performance, the length of the route is $29\frac{3}{4}$ miles, and there are only very slight gradients. The single journey, with eight intermediate stops, takes 52 mins., or an average speed of 34 m.p.h. including stops; the maximum speed being nearly 60 m.p.h. The average energy used for this service at the collector shoe is 55 Wh per ton-mile. This is based on an eight-coach train, the energy

* Metrovick Special Publication 7977/3.

being measured over the average length of station to station run, viz. 3·3 miles.*

(2) *Brighton Main Line*.—It may be contended that the 50-mile route from London to Brighton with the extension to Worthing is suburban rather than main line, for the 1½ million passengers carried annually include over 3 000 season-ticket holders; but as the distinction lies between trains stopping at every station and non-stop or junction-stop express and semi-fast services, this branch of the Southern Railway may certainly be considered a main line. Generally speaking, the work has been carried out uniformly with the suburban system described above, at least so far as the track is concerned, but some special features call for notice. A full technical description of this important electrification will be found in the supplement to *The Railway Gazette* for December 30th, 1932, from which the following details are abstracted.

Power is taken at 33 kV and 50 cycles from three substations of the National 'Grid,' and is distributed to the company's substations. Here it is converted to D.C. 600 V by mercury-arc rectifiers, operated from a Central Control Room at the halfway station of Three Bridges. The duplicate feeder cables are carried in wooden troughing on concrete poles, or in concrete troughing when below the track, and hook switches (operated manually by a rod when required) are inserted between the cables and the 100 lb. conductor rail, for isolation purposes.

The water-cooled rectifiers are in 2 500 kW, 660 V units, capable of dealing with 4 000 kW for five minutes, and are fed through delta-double-Z wound, oil-immersed, self-cooling transformers. The D.C. high-speed circuit-breakers are remotely controlled from the central control point, but can also be manually operated on the spot. For the most part, the outdoor type of main switchgear is used. The control system, though apparently complicated, is said to be very simple in action. It is operated from a 60-V D.C. duplicate-battery circuit, kept always in condition by 'trickle-charging' (§ 432, 5th ed.). By means of lamp signals and relays, full information can be obtained in the control room of the precise state of affairs in any of the remotely-controlled substations, and of the correct occurrence of any sequence of events consequent on the operator's action. The chief

* As nearly half the run, from Surbiton to Waterloo, is non-stop, the average length between stations is really nearer 1·5 miles.

difficulty to be overcome in both speeding up the services and adding to the number of trains lay in the number of important junctions met with, serving lines crossing on the level and still operated by steam.

Three-aspect colour light-signalling has been adopted, and, except at junctions, it is automatically controlled and operated by track-circuiting. Actually there are three types, *viz.*: (1) Wholly automatic; (2) semi-automatic, capable of operation from signal-boxes when open; and (3) manually operated in signal-boxes that are always open, though also automatically controlled from the track. A large proportion of the previously existing signal-boxes has been eliminated entirely; thus the new box at Brighton terminus, with 225 power-operated levers, displaced six mechanically-worked boxes with 582 levers.

New rolling-stock (46 motor coaches and trailer corridor coaches) has been designed and built for the service. Six-coach express units, including one composite Pullman, are used, two such units constituting a train during rush hours; for the semi-fast traffic four-coach units are standard, from one to three making up a train.

In place of the standard type of carriage bogies, the equalising beam type has been adopted; and an all-steel coach underframe has taken the place of the usual trussed steel underframe.

The multiple-unit system of working has been adopted throughout, for both express and fast trains, as in the case of the suburban lines, in order to ensure a speedy turn-round and clearance of the hitherto congested termini at Victoria and London Bridge. The electrical equipment of the express train units is designed to give a safe speed up to 90 m.p.h. and a maximum working speed of 75 m.p.h. Each motor coach is fitted with four 225 H.P. motors, with electro-pneumatic series-parallel control gear. Acceleration, as on the suburban lines, is automatically controlled by means of two limit relays in the driver's cab, where there are also the master controller (with standard 'dead man's handle') and also the various control switches and auxiliary controls for lighting, heating, etc. The lighting is effected through a 5 kW, 70 V motor-generator, with nickel-iron emergency batteries; the heating power is taken from the 600 V main circuit, and operates two 300 kW heaters in each compartment. The famous 'Southern Belle' express consists entirely of Pullmans; three third-class and two first-class constituting a train. For the semi-fast services, 33 four-coach units

(two motor coaches and two trailers) have been constructed. The power equipment of these consists of two 275 H.P. motors under each driver's compartment, or 1 100 H.P. for the unit, with similar control to the expresses.

922. A Miniature Freight Line.—As a further example of third-rail electric traction, the London Post Office 'tube' line may be mentioned. This two-foot gauge line has the distinction of carrying neither driver nor passengers, but only mails. The normal speed is 35 m.p.h., and there is a two-minute service with a carrying capacity of 300 tons per hour on each line, the trains consisting of three 13 ft. 6 in. cars, fitted with two 22 B.H.P. motors and running on 35 lb. rails. The brakes are applied by springs, and are pulled off electro-magnetically when the train is started. Control is effected from switch cabins at each station, where a completely interlocked system of electrical control is installed, with a visual indicator showing exactly what is happening. The working pressure is 440 V D.C. and the two 220 V motors are permanently in series, with starting resistances. A train starts from a station on a down gradient, when the section on which it is situated is energised, and approaches the next station on a dead section of rising gradient, in which the brakes are automatically applied when the holding-off solenoids are demagnetised. When the train has been brought to rest, it is restarted and run up to the platform on a reduced pressure of 150 V, so that it coasts into the station and stops, on another dead section of rail, accurately in the position required for loading or unloading. Battery locomotives are provided for breakdown purposes.*

EQUIPMENT: FEEDERS.

923. Tramway Feeders.—There is no special point about traction feeders to differentiate them from other supply feeders, except that the fluctuations in load can be more closely forecasted and the certainty of short-circuits more confidently assumed. It is usual to supply tramways with power at 500 V, generated at about 550 V either in the tramway power-house or, more often

* For a full description, see the *El. Rev.*, Feb. 10 and 17, 1928.

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now, in rotary converter substations fed from the general supply of the locality. In either case main feeders are required to transmit the power either to the line itself, or, in the case of a large system, to sub-feeders or line feeders. The function of the latter is to run along the routes and supply each separate half-mile section into which the line must be divided (§§ 909 and 911).

Although the power lost in the feeders and line has to be paid for, it is not essential to have very uniform pressure on the line; motors are not so sensitive to slight changes of pressure as lamps (§ 583). Underground insulated cables are generally used for the main feeders, and the position of the main feeding points is determined by the density of the traffic and its 'centre of gravity.' The size of the cables, subject to their capability to carry the maximum current without being damaged, is determined on economic grounds. Hopkinson's modification of Kelvin's Law is explained and illustrated in § 333 (Vol. 1), but in the case of tramways there is difficulty in assessing 'the gross annual value derived from the conductor,' though the cost of the energy wasted can be accurately forecasted.

Formulae for working out the size of overhead and underground *main feeders* on these lines will be found in specialist works on electric traction, and need not be given here; the actual process of working out tramway main feeders is a complicated one, and for project purposes it is sufficient to take a size of cable that will work at a mean current density of about 1 000 A per sq. in.,

TABLE 196.—*Pounds of Copper required for Line Feeders.*

Headway in Minutes.	Length of Track in Miles.									
	1.5.	2.	2.5.	3.	4.	5.	6.	7.	8.	10.
3	810	1 716	3 412	6 506	13 756	27 343	45 820	72 595	109 365	202 927
4	510	1 361	2 708	5 159	10 938	19 439	37 041	53 456	79 378	152 731
5	510	1 079	2 145	4 095	8 673	15 404	26 724	43 213	65 620	123 009
6	405	857	1 701	3 245	6 878	13 672	23 327	38 278	52 089	103 710
7	321	857	1 701	2 574	6 878	13 672	21 197	31 177	44 858	89 074
8	405	857	1 701	2 574	6 878	13 672	21 197	34 310	49 387	93 562
10	405	679	1 349	2 041	5 458	10 842	16 406	27 215	39 221	76 366
12	405	679	1 071	2 041	4 327	8 598	16 406	21 588	32 738	61 733
15	405	679	1 071	1 618	3 431	6 823	13 009	19 140	28 261	49 026
20	405	679	1 071	1 618	2 721	5 407	8 817	15 179	21 874	38 878

the current being found from the maximum demand in kilowatts. The Regulations of the Minister of Transport, of which those dealing with the return circuit have already been quoted above (§ 903), state in No. 11 that

In the disposition and working of feeders, the Company shall take all reasonable precautions to avoid injurious interference with any existing wires.

The *line feeders* may very often be bare overhead lines carried on the tramway poles, and their size depends on the number and weight of the cars on any one section at any given time. The amount of copper required is shown approximately in the preceding table.*

924. Feeders for Electric Railways.—So far as feeding an overhead line is concerned, the problem of railway 'line feeders' is merely that of tramways on a larger scale, modified by the fact that the contact wire of a railway may have another overhead conductor of larger section—the catenary or messenger—immediately above it. In the case of the third-rail system, the area of the conductor rail itself can be made large enough to carry the full current of the section. As with tramways, the railway line is divided up into sections—generally of one mile—electrically independent. Each section then has to be supplied by feeders either from the generating station or, more often, from a substation. A pair of duplicate cables will run alongside the track, as described in connection with the Southern Railway (§ 921), and connection will be made to the contact rail or the overhead line at the centre of each section. The feeding may be from one substation, or from the two on either side, or from all in parallel. The size of the feeders is determined from the number of sections to be fed and the calculated simultaneous demand on them, which in turn depends on the number, weight, and speed of the trains in the stretch of line and on the gradients; with allowance for regenerative braking where used (§ 900). The total load on a substation is similarly determined in order to work out the capacity of the line feeding it from the source of power.

CAPITAL COSTS.

925. Cost of Tramways.—So few new tramways are constructed nowadays that figures of cost are of little value, and

* From Dawson's *Electric Traction Pocket Book*—a most useful work of which there has unfortunately been no new edition since 1906.

TABLE 197.—*Approximate Quantities of Material Used in One Mile of Tramway Line Construction.*

Names of Pieces Used.	Cross Suspension.		Bracket-arm Suspension.		Simple Curve.		Branch Curve.		Anchorage.		One, 200-ft. Turnout.
	Single Track.	Double Track.	Single Track.	Double Track.	Single Track.	Double Track.	Single Track.	Double Track.	Single Track.	Double Track.	
Straight line insulator	46	92	—	—	— 3	— 3	— 3	— 5	—	—	—
Single pull-off	—	—	—	—	4	11	3	12	—	—	— 4
Double "	—	—	45	90	—	—	—	—	—	—	— 2
Bracket-arm insulator	—	—	—	—	—	—	1	2	—	—	— 4
Frog	—	—	—	—	—	—	5	15	—	—	—
Plain ears or clips	45	90	44	88	2	4	1	2	—	—	—
Strain "	—	—	—	—	—	—	—	—	—	—	— 8
Splicing "	1	2	1	2	—	—	—	—	1	2	—
Strain insulators	92	92	—	—	4	4	2	2	—	—	—
Insulated turn-buckle	—	—	—	—	—	—	—	—	—	—	—
" pull-off	—	—	—	—	4	4	2	2	1	2	—
Crossing	—	—	—	—	—	—	2	6	—	—	— 4
Uninsulated turn-buckle	46	46	—	—	—	—	2	—	—	—	— 4
Number of poles	90	90	45	45	2	2	1	2	2	2	— 2
Suspension wire in feet	3 000	3 000	—	—	800	800	800	800	500	500	100
Trolley wire in feet	5 280	10 560	5 280	10 560	—	—	—	—	—	200	200

those in the Third Edition, being pre-war, are entirely useless. So far as the overhead equipment is concerned, the quantities of each component remain the same, as in the Table on p. 644.

Mr. C. W. G. Taffs* gives the approximate cost, post-war, of double-track tramway as £25 000 per mile; overhead trolley wires and poles, £3 300 per mile for two wires and £4 000 for four wires—for 'trackless tramways.' He gives £2 000 as the price of a tramcar; £1 750 for a petrol bus; and £2 000 for a trolley bus.

Through the courtesy of Mr. A. R. Fearnley, General Manager of the Sheffield Corporation Tramways and Motors, the capital cost of the recent extensions to that system are given in Table 198 together with some additional costs following the table. These figures are for 4 ft. 8½ in. gauge, with girder rails weighing 112·9 lb. per yard, with concrete foundations 13 ins. thick and asphalt paving:—

TABLE 198.—*Cost of Tramway Track (Sheffield).*

	Quantity.		
		£ s. d.	£ s. d.
Excavation	2 080 cub. yds.	0 11 0	1 144 0 0
Cement concrete	1 804 " "	2 10 0	4 510 0 0
Rails	177 tons	10 12 6	1 880 12 6
Fishplates (boltless)	2·1 "	12 10 0	26 5 0
Tie bars and nuts	4·3 "	14 17 6	63 19 3
Anchors and anchor bolts	2·7 "	17 10 0	47 5 0
Platelaying (including packing and welding)	1 760 lin. yds.	0 19 7	1 723 6 8
Paving (asphalt)	4 990 sq. yds.	0 12 6	3 118 15 0
Lighting and watching	1 760 lin. yds.	0 1 5	124 13 4
Total for permanent way and paving per mile of single track			£12 638 16 9

The fishplates are welded to the rails. With the asphalt paving no parging is required. The foundations consist of a concrete bed 8 ins. thick with a finer concrete topping 5 ins. thick.

The cost of *bonding rails* for single and double track is £38 and £82 respectively per mile. (N.B.—This alone is far lower than was stated in the Third Edition, on the authority of Dawson.)

* *El. Rev.*, Vol. 92, p. 193.

The cost of *overhead equipment* for double trolley wire with cross suspension between span poles is £2 000 per mile of route.

Tramcars.—The cost of double-deck top covered tramcars with enclosed vestibule, complete double motor equipment, swivelling trolley, and air-brake equipment is £2 300 each. Of this figure the motors, controllers and resistance account for £434.

Where paving is not required it will be seen that the cost is greatly reduced.

Electricity Charges for Traction Purposes (Tramways and Trackless Trolley Systems).—The general principles relating to electricity costs and tariffs, as dealt with in Chap. 12, Vol. 1, are applicable to the sales and purchase of energy for traction purposes. A valuable paper, 'Review of Electricity Charges for Traction Purposes,' read by C. Furness before the Municipal Tramways and Transport Association (Eastbourne, 1932), deals specifically with the case for two-part tariffs for traction purposes and presents a number of detailed examples, besides useful tables of costs and charges in relation to load factor.

926. The Cost of Electric Traction: Railways.—Only the most general guidance can be given in the matter of cost of railway electrification, as no two lines are alike. It is agreed that for the overhead system the cost of substations and low-pressure D.C. work generally is greatly in excess (3 to 9 times) of that of single-phase high-pressure work, as was shown conclusively in the case of the Melbourne suburban system,* but the total and recurring costs of the latter system are far higher; especially in the matter of rolling stock (more than double) and alterations to telegraph and telephone lines (9-fold). The total recurring costs in this case (covering 300 miles of track) were estimated at £264 000 for single-phase as against £91 000 for D.C.

Trewman† gives some average prices of 1920, but they are lower now; £9 per kW as a fair overall price for complete substations would be considered high now except for small plants. 'A fair average figure for third and fourth rails, complete with insulators, protecting boards and feeder cables for sectionalising purposes, laid ready for service, would be about £4 000 per mile

* 'The Times' Engineering Supplement, Nov. 20, 1912, quoted by F. W. Carter in *Railway Electric Traction* (1922).

† *Railway Electrification*, by H. F. Trewman, p. 58 *et seq.*

of single track.' The same writer puts the cost of coach bodies and trucks at £100 per ton and of electrical equipment of the same at £200 per ton for all systems which, taking into account the greater weight of single-phase equipment, works out to some £64 per foot length of the average train hauled for the latter system against £54 for D.C.

A description of the main features of the electrification of the Great Indian Peninsular Railway has been given above (§ 918); and through the courtesy of the High Commissioner for India and the India Store Department some general figures of the cost of this work are here added.

Transmission lines (110 000 V) as described, including erection: double circuit, £1 730 per mile; single circuit, £1 088 per mile.

Substations complete (exclusive of all building work) average £34 900 each, or £16 700 per 2 500 kW rotary installed = £5.9 per kW.

Track-sectioning cabins and corresponding gear in the controlling substations, £1 895 each, exclusive of building work.

Overhead track equipment:—

- (i) For tangent running tracks (1 sq. in. equivalent) with tension lengths of 1 mile anchored at both ends, and with girder construction, £3 798 per mile of double track, exclusive of foundations.
- (ii) The same with cantilever construction, £4 397 per mile of double track.
- (iii) The same as (ii), but with half-mile tension lengths, £4 640 per mile of double track.
Additional for curves, £400 per mile for (i), £806 for (ii), and £687 for (iii).
- (iv) For 0.5 sq. in. equivalent, the cost is £1 733 per mile of single track, with £200 extra on curves.

Turn-outs, cross-overs, junctions, etc., and special equipment for sectioning, tensioning, and bridge or tunnel work involve additional expense; and the above does not include the cost of the low-pressure control wires. Where a 22 000-V line is carried on the structures, the cost for a double circuit 3-phase line of 0.15 sq. in. is £1 339 per mile; with underground cables the same costs £1 880.

For *passenger locomotives* the mean price of three makes is

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£13 170, equal to £207 per ton gross, a spare motor costing £788 mean.

Freight locomotives cost £15 400, equal to £130 per ton gross.

ELECTRICITY IN VEHICLES.

927. Uses of Electricity in Vehicles: Lighting.—Any vehicle, whether running on rails or on the roads, and whether actuated by electricity or not, may use electricity for such subsidiary purposes as are necessary; on tramways and road vehicles for lighting and heating; on railways, in addition to these, for cooling and for ventilation by fans, where the climate necessitates this; and on all, for work in substitution of human muscles, as in control or servo-motors for braking, etc. Where the line is an electric tramway or railway, power is, as a matter of course, taken from the line; where self-contained vehicles are in question, with a battery or petrol-electric drive, the power will be taken from this source; but in the case of non-electric vehicles, the power must be generated specially for these additional services (§ 929).

Lighting.—At the present time the scale of electric lighting on vehicles of all sorts is improving year by year, though gas and even oil lighting are still to be found on some railways, especially abroad; and, while the floating wick is inexcusable because of its utter inadequacy, gas is likely to be prohibited in the long run on account of its danger, as evidenced by the pointed and repeated recommendations of the Board of Trade in enquiries relating to accidents.

Vehicle lighting introduces the questions of pressure variation and of vibration. Vibration cannot be obviated, but lamps have been designed to stand up to it, with special filaments mounted in a castellated form. Where power from the line is used, pressure variation inevitably occurs, both from the variation of the load generally and during acceleration of the vehicle in particular; this, however, is an inherent defect which becomes less serious as the design of the circuit and the control gear of the vehicle are improved. When power is obtained from a self-contained generator and battery, there need be no appreciable variation. The third case, of special systems, is dealt with in §§ 929 *et seq.* On the standard tramway pressure of 500 V several lamps are used in series, as also on electric railways run at higher pressures, except

where the use of A.C. enables low pressure to be obtained from transformers. Self-contained vehicles and those supplied from special systems (§ 929) use very low pressures—20 to 50 V, generally 24 V.

The illumination provided in modern rolling stock leaves little to be desired, especially by those who remember the Metropolitan Railway in its steam days; * from 2 to 4 or even 5 ft.-candles (§§ 579, 580) may be found, in contrast with the utterly inadequate beacons found on most station platforms above ground. Naturally in the driver's cabin there will be no light except a subdued one over the dials of instruments. There is still room for improvement in the matter of fittings and shades; unshaded metal filaments, almost on a level with the eyes of passengers, are bound in time to have a deleterious effect on eyesight, and they are still far too commonly used. The variation in line voltage, and consequently in candle-power, is annoying but unavoidable.

928. Uses of Electricity in Vehicles; Ventilation and Heating.—While lighting, at its best, requires very little power, other electrical amenities use a considerable amount.

Electric Fans.—In tropical countries, fans are provided at least in refreshment cars and in the higher classes on main-line trains, and their use will spread slowly to branch lines and 'third class.' For this service moderately high-speed, small diameter fans are used requiring from 30 to 60 W each, of the ceiling or desk type. Their effective radius of direct draught is comparatively small, so in compartments they are usually so arranged that they can be swivelled into the best position for the individual passenger; their chief function being (in India, at any rate) to keep off mosquitoes. In saloons and refreshment cars they are naturally fixed, and keep up a sufficient circulation to counteract a humid atmosphere at something over 100° F. The use of air ducts, supplied from pressure fans, as on modern P. and O. steamers, has so far not come into use elsewhere.

Electric Heating.—For heating tramcars or railway compartments electricity is only likely to be used—as it is now used—when power is available from the line; the demand would generally be too great to be met by plant carried on board.

* Foul smelling oil gas was used, obtained by an early application of 'cracking.'

Except for the fact that the heating elements must be concealed and placed so that by no possibility can they set light to the coachwork, or to passengers' clothing, the considerations in Chapter 26 (Vol. 2) apply. Attention may, however, be drawn to § 625 in that chapter for a special case of heating railway vehicles; on the London and North-Eastern Railway a 400 kW Bastian boiler, with immersion heaters (§ 617, 623), is used to supply steam at the rate of 1 175 lb. per hr. and a pressure of 120 lb. / sq. in. for heating rolling stock when running over the electrified portion of the line.

Electric Cooking.—The kitchen of a railway train differs in no particular way from one on *terra firma*, though here again the power required confines its use practically to vehicles on which the line current can be used. In the course of the enquiry into the Charfield railway disaster, 1928, in which, as usual, the ignition of the gas cylinders intensified the horror, it was stated by a railway official that 'it would be impossible to provide the necessary meals by electric cooking.' This statement, like the meals in question, requires to be taken *cum grano salis*. (See Vol. 2, paragraphs 530, 574, 628, 629, 632, 633.)

929. Generation of Power for Use in Railway Carriages.—Where power is not obtainable from the line, *i.e.* on steam railways or non-electrical self-contained vehicles, there are various alternative methods of obtaining the power required for subsidiary purposes, namely: (a) secondary batteries, (b) self-contained generating units, or (c) special systems of axle-driven generators; the two latter nearly always in conjunction with batteries.

Batteries.—Even lighting, from batteries alone, necessitates considerable capacity in the cells and involves the provision of special charging stations at various points in the system, where the batteries have to be taken out and replaced by properly charged duplicates. Thus, even allowing for the diversity factor, there will need to be almost twice as many batteries as vehicles, to allow for repairs and replacements. The system is therefore of very limited use, and of none on main lines.

Self-contained Generating Sets.—In the second method, power may be generated on the engine, and transmitted throughout the train, or each carriage may have its own self-contained equipment. Thus small steam turbo-generators are used for working a head-light (*i.e.* an arc lamp with a parabolic reflector behind it) on

some Indian and American railways; * and a similar arrangement of plant can be used for lighting and ventilating purposes. Petrol engine sets can also be used for this purpose, as on motor-cars and petrol-electric vehicles (§ 953). Generally, however, a battery is carried on each vehicle or unit and run in parallel with the generator; this enables the set to be shut down during the day, the batteries taking the load in tunnels, and affords both reserve and better regulation. With such small sets the efficiency is inevitably low, and the expense therefore considerable, as the set requires attention all the time.

Axle-driven Systems.—The most usual, and also the most flexible, method is to have both an axle-driven generator and a battery working in parallel with it, on each vehicle; the battery taking the load when the train is standing and assisting in the regulation of the pressure when the train is running and charging it. This necessitates automatic operation regardless of speed or direction of running; automatic and correct charging of the battery without injurious overvoltage at the lamps; lightness, durability and immunity from damage or derangement by moisture, smoke or (in the tropics) insects.† Constant-current or constant-power regulation (§ 948) involves the risk of overheating the electrolyte and injuring the cells, unless a charge-limiting device is used; constant-voltage regulation involves the risk of under-charging on the one hand and, on the other, of excessive initial charge when the battery is nearly run down. Above all, the arrangement adopted must be 'fool-proof' if it is to be used in a country where skilled attention is not always to hand.

A good many automatic train-lighting systems have been patented, many of them very ingenious; an ordinary dynamo, driven off the carriage axle, would vary its E.M.F. according to the speed of the train; the problem is to design a generator which will keep its E.M.F. constant under these conditions.

In a paper by T. Ferguson (*Journal I.E.E.*, Vol. 52, p. 262)

* Incidentally the driver is often practically blinded by the glare reflected from myriads of white moths attracted by the light.

† The ways of the termite, the greenfly and certain wasps are past all comprehension; between them they can derange almost any piece of machinery, except perhaps a steam-hammer, but especially relays and apparatus of the telephone order. See 'Telephone Troubles in the Tropics,' by W. L. Preece. *Jour. I.E.E.*, Vol. 53, p. 545.

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the following systems are described, *viz.*: Stone; Leeds Forge Co.; Mather & Platt; Vickers; Tudor Accumulator Co.; Silver-town; Brown Boveri; Dalziel; Grob. The author summarises the conditions demanded of train-lighting systems as follows:—

1. The equipment may have to run on night service for long periods; hence the dynamo while running must generate more current than is required for the lamps, that is to say, it must charge the battery while the lamps are burning, in order to make up for the current taken from the battery to supply the lamps while the train is stationary, and also to make up for the local losses which take place within the battery.

2. The equipment may similarly have to run on day service for long periods; hence some definite means for the adjustment of the output is necessary.

3. The same equipment may have to run on a suburban service having many stops and a low average speed, or an express service with few stops and a high average speed. It would be a great drawback if the ratio of the pulleys had to be changed when passing from the one type of service to the other. On most railways the traffic department is not slow to raise objections if this has to be done. A train-lighting dynamo should be capable of operating satisfactorily between speeds of 12 and 72 m.p.h. in order to make it sufficiently flexible in working.

4. Machines are required both for coaches requiring heavy and light lamp-loads, and as it is inadvisable to use many different sizes, some form of output adjustment is again necessary.

5. The storage battery cells must be as few as possible, on account of first cost, subsequent maintenance, and 'dead-weight.'

6. The equipment must be robust, simple, strong, obvious in action, and easy of definite adjustment, so that poor-class labour may be able to maintain it.

7. The maintenance cost must be as low as possible both as regards the dynamo and the batteries.

8. It should be possible to switch the lamps on and off at will without affecting the voltage applied to the lamps remaining burning.

9. The output must be easily and definitely adjustable to suit all conditions of traffic.

10. The additional draw-bar pull on the locomotive due to driving the dynamos must be as low as possible, especially at high speeds.

11. Batteries which have got into bad sulphated condition, owing to coaches lying idle, must quickly pick up again when the coaches are placed in service.

930. Stone's Train-Lighting System.—In the Stone system, which is used on almost all Indian railways on account of its simplicity, there are *two sets* of batteries suspended on the under-frame, one or the other of which supplies current when the train is standing or running slowly. The dynamo is suspended by one corner of its frame, by means of an adjustable link, so that it is free to swing towards or away from the driving pulley on the carriage axle. The driving belt draws the dynamo out of the diagonal position in which it would naturally hang, and the

tension on the belt thus automatically adjusts itself to the power required. When the speed of the train during acceleration reaches a predetermined value an automatic cut-in and cut-out switch puts the dynamo into circuit, and when this speed is passed in slowing down the cut-out disconnects the dynamo.

If the train speed increases beyond a certain point, or the demand drops, the belt slips and the armature continues to revolve at about its correct speed and to give approximately the correct volts. The dynamo supplies power to the lamps and fans while the train is running, and also automatically charges one of the batteries while the other 'floats on the load' and acts as a regulator. Reversals of train direction are met automatically. The usual pressures of supply are 16 or 24 V, requiring two batteries each of eight or twelve cells. Owing to the fact that the cells are always kept fully charged, and that there is no sensible drop of pressure in the short conductors, extra regulating cells are not needed.

931. Mather & Platt Train-Lighting System.—In the Mather & Platt system single or double batteries are used in conjunction with a self-regulating axle-driven dynamo, which cuts in and out at a pre-determined speed. The regulation is inherent in the dynamo design, and no matter how the speed may vary above the predetermined cutting-in limit the voltage remains practically constant; there are no external regulating devices, and the direction of the current does not change when the rotation of the armature is reversed, so no pole-changing device is required. This result is obtained by very ingenious design. The field magnet, usually two-pole, is excited by a shunt winding of comparatively few ampere-turns, connected to the dynamo terminals in the usual manner. The cells are, as usual, in parallel with the main circuit. The pole pieces are of normal construction, but the pole limbs and yoke, which complete the magnetic circuit (§ 41), are of much smaller cross-section than they would be in an ordinary dynamo of the same size. The armature is of the drum type and connected to the commutator in the usual manner. The self-regulating properties are due to the peculiar arrangement of the brushes, coupled with the easily saturated magnetic circuit. The brushes bearing on the neutral point, which in an ordinary machine would supply current to the external circuit, are short-circuited, and a second pair of 'aid' brushes at right angles to these constitute the main

working brushes from which current is led to the lamps, etc. A very small magnetic flux in the field magnet is sufficient to produce a large current from brush to brush in the short-circuited path; this current, circulating in the armature conductors, produces a magnetic flux at right angles to the ordinary flux, circulating *only* through the iron of the pole pieces and armature and *not* through the pole limbs or yoke. The rotation of the armature in this secondary flux produces a difference of potential in the secondary brushes and thus gives the working current. The limit is reached when the main current exactly neutralises the effect of the field winding, and this limiting current cannot be exceeded under any conditions whatever for any given excitation in the field windings, since the combination of the flux due to the shunt winding and that due to the short-circuit current is so

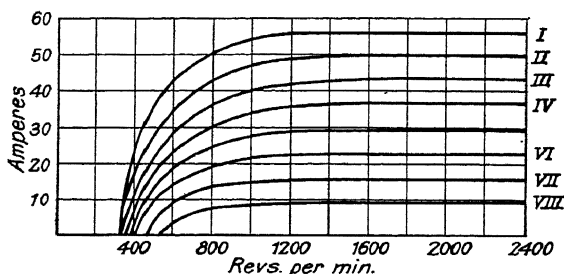


FIG. 410.—Characteristic curves of Mather & Platt train-lighting dynamo.

adjusted as to give a practically constant external current at all speeds. If the direction of rotation is reversed the short-circuit current is also reversed, and as the primary flux is unaltered in direction the working current will circulate in the same direction as before.

The characteristic curves of this dynamo, when working in parallel with a battery at constant voltage, under various excitations, are shown in Nos. I. to VIII. of Fig. 410. A special battery cut-in and cut-out switch is of course necessary.

Two systems of train lighting employing the above principle are in use, known as the 'simplified unit system' and the 'parallel block system.' In the former, each dynamo with its 24-V battery—or pair of 12-cell batteries in parallel—supplies its own independent load without any interconnection between one carriage and another. For this the dynamo has an additional series field

winding, connected in the common negative return which must be provided for the whole load. The shunt winding is so set by means of an 'output adjuster' rheostat as to give the desired charging current for the battery, which is then independent of the external load; the series coil is so proportioned that every additional ampere in it increases the dynamo output also by the same amount.

In the parallel block system, all the vehicle units of dynamo and 12-cell duplicate battery, etc., are in effect paralleled on to a set of 24-V bus-bars running the whole length of the train. The train can be broken up and remade, with other systems (of the same standard train voltage) on some of the coaches. The output is adjusted by a shunt regulator. When the dynamo is running and lights are in use, the batteries are paralleled through a buffer 'lamp resistance'; but when the train is stationary, they are directly paralleled by the cut-in switch or the lighting switch.

932. The Dick (Siemens-Schuckert) System.—The Dick system* claims to fulfil the conditions of the required service more fully than others; but it is not known to what extent it is in actual use, and this is the acid test of any system so exacting in its requirements. In the accompanying illustration (Fig. 411),

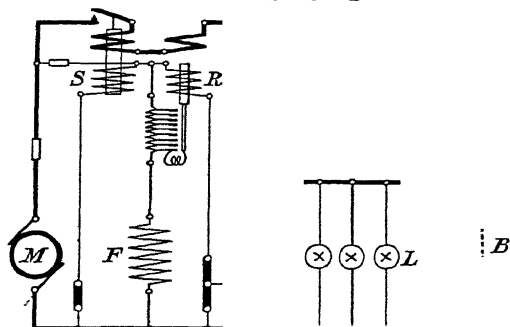


FIG. 411.—Diagram of connections of Dick train-lighting system.

M represents the armature of the axle-driven dynamo; F its field winding; B the battery; L the lamps; R the automatic shunt regulator; S the automatic switch disconnecting the machine at speeds below the critical value (15 to 18 m.p.h. on main lines); and H is the main lighting switch. Above the critical speed and

* *Elektrotechnik und Maschinenbau*, Vol. 41, p. 200, April 1, 1923.

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up to from 50 to 70 m.p.h. the field regulator maintains a constant limiting voltage. The value of 2·4 to 2·5 V per cell is reached only with a fully-charged battery and with the lamps switched off, independent of speed; the charging current then becomes 5 or 10 % of normal, and the cells cannot be injured. With the lamps on, or the battery discharged, the auxiliary series winding on the shunt regulator reduces the dynamo voltage to 2·2 or 2·3 V per cell, thus preventing the machine from being overloaded.

TRAFFIC CONTROL.

933. Electric Signalling on Railways.—For the last thirty years the 'block system' of signalling has been compulsory on all British railways, which accounts for their exceptional freedom from accidents due to the human element. The system has been developed gradually, by the elimination of points found weak in practice, and in the matter of communication between signals-boxes the telegraph has always been used. The controlling mechanism of points and signals is always so interlocked as to prevent more than one train being within a block at any one time. Then, with increasing density of traffic, electrical track signalling followed, enabling, *inter alia*, the danger of a detached vehicle remaining in a block to be guarded against. With the advent of 'tube' railways, full electrical signalling and automatic systems have followed, constituting an extremely important minor branch of railway electrical engineering on both steam and electric lines.* Of late years light signals have grown in favour, as against semaphores, and extensive installations of this kind have been carried out on both classes of line.

The signalling on the London 'tubes' is all electrical automatic track-signalling, using coloured lights exclusively. In connection with the remodelling of the Victoria and Exchange stations at Manchester, the London, Midland and Scottish Railway has also installed electric signals in conjunction with the Westinghouse Brake and Saxby Signal Co. Here the installation includes three new signal-boxes with a total of 209 levers, 128 electrically-driven point machines, over 200 colour light signals of four, three, and two aspects, 26 optical route indicators, and 176 alternating-

* An excellent elementary summary will be found in 'Electrical Signalling Equipment on Railways,' by S. Mitchell. *Jour. I.E.E.*, Vol. 62, p. 954.

current condenser fed track circuits. The point machines are worked by direct current derived from the alternating-current mains by means of Westinghouse metal rectifiers, consisting essentially of a series of copper discs having one side oxidised to cuprous oxide.

By way of more detailed description, the electrical signalling arrangements adopted in the remodelling of the Charing Cross and Cannon Street stations of the Southern Railway may be referred to :—*

For the new signalling it was decided to install an all-electric power system, with colour light signals, the whole area dealt with being divided into track-circuited sections for automatic and semi-automatic block working in substitution for the existing 'lock and block.' This was thought to be the best method for dealing with the very dense traffic which prevails during the morning and evening rush hours.

New signal-frames, the levers of which are of the miniature type, have been provided at both Charing Cross and Cannon Street stations, and the usual mechanical locking is provided.

Immediately behind each lever is a small light repeater, which indicates the effect of the operation of the lever. In the case of the running-signals the four aspects—green, double yellow, single yellow, or red—are repeated one at a time in accord with what is shown at the signal. Similarly, two small lights, green and red, are provided behind the shunt signal-levers. The letter 'N' or 'R' appears behind the point-levers according as the points lie 'normal' or 'reverse,' and if the points are in neither of these positions, the indicators show blank.

An illuminated track-circuit diagram, showing the whole of the lines, points, and signals controlled from the signal-box, is fixed at the back of the frame in full view of the signalmen, and by this means the signalmen see the condition of the line as regards traffic over the whole area they control.

Two sources of electric supply have been provided, namely, alternating current for the lamps in the light-signal aspects, the track-circuits, and the electric locking in the frame, and direct current for working the point-movements and the route-indicators. A second source of power for the point-movements, consisting of two 70-cell accumulators, has been arranged for, in case of emergency.

In the automatic sections, the signal-aspects are controlled by the conditions of the road ahead, and normally show green. Within station limits the roads are normally blocked until the signal-lever is reversed, after which the signal-aspects are automatically controlled by the track-circuited sections ahead. If the block section immediately ahead of a signal is occupied, the signal remains red; if one section ahead is clear, a single yellow light will be exhibited; if two sections ahead are unoccupied, a double yellow light will be seen; and if three or more sections ahead are clear, the green light will be displayed. The information thus conveyed to drivers enables them to control the speed of the trains with a greater degree of flexibility than is the case with three-aspect signalling.

* 'The Remodelling of Charing Cross and Cannon Street Stations,' by George Ellison; abstracted by kind permission of the Author and the Institution from *Progs. Inst. C.E.*, Vol. 223, p. 172 *et seq.*

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The light signals can easily be seen by day and by night, and to provide against a light going out, when no signal would be exhibited, each incandescent lamp has two filaments, placed very nearly in the focus of the lens, which burn together. If one filament burns out, a reduced light is given, and drivers call attention to the fact. At the same time, the lamp takes less current, and this is arranged to dim the lamp in the indicator behind the lever in the signal-frame, which calls the signalman's attention to the matter.

In the single-rail track-circuits one rail is insulated and set aside entirely for the track-circuit, the other rail being used in common by the track-circuit and the traction

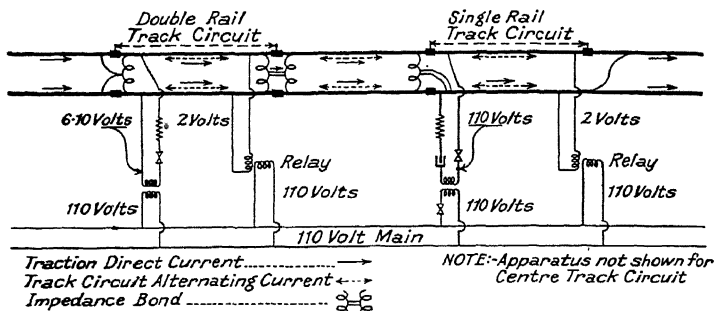


FIG. 412.—Southern Railway: Diagram of typical track-circuits for signalling.

currents for their respective returns. The track-circuit current is taken direct from the main to a transformer and thence through a variable condenser to the feed-rail. It then passes to the relay end of the track-circuited section and back by the opposite or return rail to the feed end, which is connected to the other terminal of the transformer (see Fig. 412).

In the double-rail track-circuits two or three resonated impedance bonds are used to allow the return traction current to pass through both rails without interfering with the track-circuits.

934. Bibliography.—(See explanatory note, § 58, Vol. 1.)

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See also § 955 for Tramway and Trolley Bus References.

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No. 9.—Bull Head Railway Rails.

No. 11.—Flat Bottom Railway Rails.

No. 23.—Trolley Groove and Wire.

No. 24.—Railway Rolling Stock. *Part 1.* Locomotive, Carriage, and Wagon Axles. *Part 2.* Locomotive, Carriage, and Wagon Tyres. *Part 3.* Laminated, Volute, and Helical Springs, and Steel for Laminated Springs. *Part 4.* Steel Forgings, Blooms, and Castings. *Part 5.* Copper Plates, Rods, Tubes and Pipes, and Brass Tubes. *Part 6.* Steel Plates, Angles, etc., and Rivets for Locomotives, Carriages, and Wagons.

No. 47.—Steel Fishplates.

No. 51.—Wrought Iron.

No. 64.—Fishbolts and Nuts for Railway Rails.

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No. 79.—Special Trackwork for Tramways.

No. 101.—Tramway Tyres.

No. 102.—Tramway Axles.

No. 103.—Falling Weight Testing Machines for Rails.

No. 104.—Light Flat Bottom Railway Rails and Fishplates.

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No. 150.—Cast Steel Wheel Centres for Electric Tramway Cars.

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No. 235.—Gear Wheels and Pinions for Electric Tramways.

No. 376.—Railway Signalling Symbols. *Part 1.* Schematic Symbols.

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No. 469.—Electric Lamps for Railway Signalling.

No. 484.—Rolled Steel Disc Wheel Centres for Electric Tramway Cars.

CHAPTER 36.

ELECTRIC ROAD VEHICLES.

935. Types of Electric Road Vehicles.—The vehicles considered in this chapter differ primarily from those discussed in the two preceding chapters in that they run on the ordinary road surface instead of on rails. Starting from the tramcar, we may fit this with rubber-tyred wheels and provide for it a second overhead line and trolley boom (in place of the rail-return circuit), and the car will then be able to run on the ordinary roadway. It becomes, in fact, a *trackless trolley-bus* (§ 954), and though it has valuable manœuvring powers in traffic on a particular road, it is restricted to routes on which trolley wires are provided. Now trolley wires are costly to erect (§ 925), and the outlay may not be justified. For general service we may go further and dispense with the overhead lines (which bring energy from the central station) by providing a generating station on the vehicle itself in the form of a petrol-driven dynamo. We have then a self-contained *petrol-electric vehicle* (§ 953). A third alternative is to carry a store of potential electrical energy on the vehicle by using accumulators or storage batteries, in which case we have a *battery vehicle*—self-contained so far as its actual running is concerned, but dependent on a central station or private generating plant for periodically recharging its battery. The electrically-driven vehicle has so far not made the headway in Europe which might have been expected from its extended use in the U.S.A. Though the radius of action of battery vehicles is restricted, they have great advantages within that radius, especially if it is congested. The petrol-electric vehicle does not suffer from this limitation, and shares with the former the quieter running which is due to the absence of a gear-box. A further recent advance, shared by all sorts of road vehicles, is the

use of a servo-motor for semi-automatic braking; the servo-motor provides most of the effort needed, while the driver can, without effort, regulate the precise amount of effort required.

In the case of non-electric heavy road vehicles, the 6-wheeled truck is coming into extensive use, both in the 'rigid' and 'articulated' types; and electrics are following suit. The main object is to enable surfaces to be negotiated that would be difficult with the usual four wheels; but on smooth track the extra wheels enable heavier loads to be carried, as there are often restrictions as to the permissible load on one axle for crossing bridges not built for modern traffic. *The Times* 'Review of Commercial Motor Vehicles, 1928,' also calls attention to an 8-wheeled lorry, with a total weight of $7\frac{1}{2}$ tons. Another tendency is towards dropping the frame, so as to give a lower centre of gravity, increase the margin of safety, and expedite loading and unloading.

936. Battery Vehicles or 'Electrics': General Description and Advantages.—The essential parts of a storage battery vehicle (apart from the frame, body, and wheels of the vehicle itself) comprise a battery of storage cells, an electric motor, an electric controller, the necessary electrical connections, and mechanical connections between the motor and road wheels. Defects in storage cells and the application of battery vehicles to unsuitable classes of service were responsible for most of the failures in early experiments with these vehicles. Unfortunately these failures gave battery vehicles as a whole a bad name in many quarters. However, very satisfactory traction batteries are now available, and the battery vehicle is thoroughly established in America and may be expected to gain ground in this country as facilities for battery-charging become more general. The outstanding merits of the 'electric' (this term being a convenient and accepted abbreviation for the cumbersome name 'electric storage battery vehicle') are its simplicity and durability. Its chief disadvantages are limited mileage per battery-charge (§ 937) and high first cost. The latter disadvantage is sure to be removed as manufacture becomes standardised and wider in extent. It is doubtful whether the economically practicable mileage per charge for a passenger car will be increased, in the near future, much beyond 60 or 70 miles, so that the practicability of touring by 'electric' depends on the development of suitable battery-charging facilities all over the country (§ 950). In the meantime the most advantageous applica-

tion of electrics is to commercial, industrial, and municipal service in and around towns. For such work 40 or 50 miles per charge is ample, and in delivery work or in traffic, where starting and stopping are frequent, the smooth and rapid acceleration of electric vehicles gives them a higher average speed than petrol vehicles which have considerably higher maximum speed. There is no current consumption and no machinery in motion when an electric is standing still. The electric vehicle is clean, safe, and silent. It has few mechanical parts, and those are simple. The electric motor is a much simpler and more durable machine than the petrol engine, and the electric vehicle needs no clutch, change gear-box, carburettor, magneto, sparking plug, cooling fan, oil pump, radiator, or water-cooling system; further, it requires no store of highly inflammable fuel. No special skill is required to drive an electric, and the vehicle cannot be 'overdriven' to the detriment of the tyres and mechanical parts. Due to automatic fall in speed of the motor on increasing load, and to the high overload capacity of motor and battery, the hill-climbing capabilities of an electric are excellent. Its smooth acceleration favours long life of tyres, and due to this and to the simplicity and durability of the mechanical components, the overall depreciation on an electric is low, and modern battery vehicles may be expected to last at least 15 years and run 150 000 miles or more. There are already many vehicles in service which are more than 20 years old and the majority of modern electrics are likely to last as long. Energy is obtainable at low prices from central stations (§ 950), but does not represent a large fraction of the total operating cost (§ 947). Interchangeable bodies can be used conveniently, whether to adapt a heavy chassis to different industrial or municipal services, or to convert a light delivery van into a passenger car.

The dead-weight of the battery carried may be set against the weight of clutch, gear-box, and other equipment essential to a petrol car but unnecessary on an electric (*see also* § 938). The petrol car has undoubtedly the advantage in point of maximum speed and range of action. A 1 260-lb. nickel storage battery suffices to drive a 1-ton electric, say, 50 miles (§§ 939, 946), whilst the same weight in petrol (corresponding to 160 gallons) would drive a similar petrol vehicle, say 2 400 miles; actually, only 10 to 15 gallons of petrol would be carried, and the dead-weight of this averages only *half* the weight of the tankful, whereas a battery

vehicle has always a heavy battery as dead-weight.* A fresh supply of petrol can be obtained almost anywhere in the country, and the weight of a spare 2-gallon tin for emergency use and sufficing for 20 to 40 miles' running is only about 18 lb. For long-distance high-speed work the petrol car is unrivalled, but for 'short haul, frequent stop' service the electric battery vehicle is the better, both in point of average total cost per ton-mile and in point of average speed (including stops). Considerable skill is required to drive and maintain a petrol vehicle, and the large reserve of power necessary for hill-climbing (due to the negligible overload capacity of a petrol engine) is liable to be misapplied to obtaining excessive speed on the level, with results disastrous to vehicle and road alike. This consideration is specially serious where commercial vehicles are concerned; for them an average speed from 8 to 15 m.p.h. (according to weight) is all that is necessary or desirable.

937. Electric Vehicle Service Data.—Trackless trolley-buses (§ 954) are limited to public passenger service, and petrol-electric operation (§ 953) is practically confined to heavy passenger-carrying or industrial vehicles, but storage battery propulsion is applied to an immense variety of vehicles ranging from small trolley-trucks up to the heaviest industrial wagons. Leading particulars of a number of typical electrics are given in Table 199. It will be seen that the pleasure vehicles range from electrically propelled bath-chairs to five-seat touring cars capable of 20 to 30 m.p.h. on level roads. It is incorrect to suppose that electrics are incapable of high speed; battery cars have been built for speeds exceeding 60 m.p.h., but naturally the battery has had to be large and unduly heavy to obtain any useful mileage per charge. For ordinary service the speeds and mileages shown in Table 199 represent a reasonable compromise. Industrial electrics range from low auto-trucks, suitable for taking goods from point to point in workshops, warehouses, railway stations, or on wharves, up to the heaviest lorries and tractors capable of dealing with 5 to 10 tons useful load. The sizes of commercial van most generally useful have from $\frac{1}{2}$ to 2 tons loading capacity. Battery-propelled fire-escapes, ambulances, dust and water carts, road sweepers, and tower

* This comparison must not be made the basis of conclusions regarding the relative *total* dead-weights of petrol and battery vehicles. That matter is dealt with in § 938.

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wagons deserve mention. It should be noted that the battery provides energy for operating motor-tipping wagons, for operating portable cranes and machine tools on breakdown jobs, and for demonstration purposes when canvassing householders and others with a view to persuading them to make use of electricity supply.

The maximum speeds and mileages given in Table 199 are only

TABLE 199.—*Typical Particulars of Electric Battery Vehicles.*

Description and Useful Carrying Capacity.	Maximum Speed on Level, m.p.h.	Mileage on One Battery Charge.
Bath chair (1 or 2 persons)	4-10	30
Town coupé or cab (4 or 5 persons)	15-25	40-60
Roadster (2 to 5 persons)	20-30	55-70
Shop, yard, or railway goods-handling truck ($\frac{1}{2}$ to 5 tons)	1-7	25-30
$\frac{1}{2}$ -ton parcel-carrier (3 or 4 wheels)	15-20	50-70
$\frac{1}{2}$ -ton van (3 or 4 wheels)	12-15	45-55
1-ton van	10-14	40-50
2-ton van	8-12	35-45
3-ton lorry	7-10	35-40
5-ton lorry	6-8	35
Ambulance (cf. $\frac{1}{2}$ -ton van)	15-20	30-50
Water cart	5-10	40
22-passenger, 1-deck bus	12	40-50
1-ton tower wagon	12	50

approximate; much depends on the circumstances of each case and on the battery employed; by reducing the maximum speed somewhat a useful increase in mileage can often be obtained (§ 941). Except in the case of passenger cars, cabs, and buses, modern battery vehicles can generally cover the average daily mileage required on a single battery charge. When this is the case, the battery can be recharged during the night under favourable conditions and at favourable prices for current supply; otherwise, the battery must be replaced by a fully charged one after doing half a day's work, or the deficiency in battery mileage may be made good by a special 'boosting' charge (§ 949), this alternative being preferable. The annual mileage of pleasure cars is quite indeterminate; that of commercial vehicles varies widely, but may be taken to average 10 000 or 11 000 miles per annum in the case of $\frac{1}{2}$ - to

1-ton delivery vans, and 5 000 to 7 000 miles per annum in the case of 4- or 5-ton lorries. A bus running in city and suburban service may travel 25 000 to 35 000 miles per annum. The annual mileage of ambulances, fire-escapes, and other special vehicles is often quite small; it is the fact that an electric vehicle is ready for instant use at any time which makes it particularly valuable in such applications.

938. General Arrangement of 'Electrics'; Dead-Weight.

—It is frequently impossible to tell an electric from a petrol-driven vehicle by casual inspection of its external appearance, the main structural features (frame, springs, road wheels, steering gear, etc.) and their arrangement being essentially the same in each case. Sometimes the electric vehicle has no 'bonnet'; sometimes it has quite a shallow one, containing and giving access to the controller and dashboard instrument connections; and sometimes it has a full-sized bonnet, beneath which are located some or all of the battery cells. Other positions for the battery are under the driver's seat and in a frame slung under the centre of the chassis. It is convenient to be able to run the cells out quickly for inspection or replacement, but they are generally charged *in situ*. Unless front-wheel drive is employed, the motor is generally placed half way along the main frame or else near the back wheels, according to the precise type of mechanical transmission employed (§ 944). Solid rubber tyres are generally used on commercial electrics, and, due to the smooth acceleration and running of these vehicles, tyre-makers' guarantees of 10 000 to 15 000 miles' life are often exceeded. It is well worth while to use nothing but the best materials and construction and ball or roller bearings throughout electric vehicles.

Though the battery constitutes quite a serious dead load in any storage battery vehicle—say 7 to 11 cwts. in light vans carrying up to $\frac{1}{2}$ ton useful load, and 1 to $1\frac{1}{2}$ tons in a 4-ton waggon—there is considerable saving in other directions (§ 936). Typical values of dead-weight in terms of useful load are given in Table 200.

As might be expected, the weight of the battery (and hence the total dead-weight) is relatively more serious in small than in larger vehicles. In very light commercial vehicles (up to 750 lb. useful load), nickel accumulators may represent 35 to 40 %, and lead cells 45 to 55 % of the total dead-weight; whilst in larger

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TABLE 200.—*Dead-Weight and Useful Load in Electric and Petrol Vehicles.*

Useful Load. (Tons.)	Dead-Weight / Useful Load.	
	Electric Vehicles.	Petrol Vehicles.
$\frac{1}{4}$	5 to 7	3
$\frac{1}{2}$	3 „ 4	2
1	2	$1\frac{3}{4}$
2	$1\frac{1}{2}$	$1\frac{1}{4}$
3	$1\frac{1}{4}$	1
5	1	0.8

vehicles the battery accounts for 25 to 30 % of the dead-weight, using nickel cells, or 35 to 40 %, using lead cells. Steam wagons are at least as heavy as corresponding electric wagons, and often heavier when the weight of fuel and water carried is taken into account.

939. Lead and Nickel Traction Cells: Characteristics and Life.—The present importance and value of battery vehicles depend fundamentally on improvements made in storage cells during recent years. The pasted lead-plate batteries used about thirty years ago, in the early days of the motor-car revival in this country, weighed over 1 cwt. per H.P.-hour of energy stored (corresponding to 6 Wh per lb.), and required fresh plates after 100 or so cycles of charge and discharge. The latest lead traction cells weigh 60 to 85 lb., and the Edison nickel cell (§ 434) about 50 lb., per H.P.-hour; the life, in cycles of charge and discharge, being 600 to 700 or more for lead cells and 1 500 or more for nickel cells. As compared with the former figure, these values of weight per H.P.-hour represent a marked advance—an advance, it is true, less considerable than had been hoped for, but one which has demanded infinite labour for its attainment. The improvement in mechanical strength of storage batteries has been more notable. Lead-plate batteries, as now constructed specially for traction work, may be expected to run 15 000 miles, and even 25 000 miles or more if treated well, before fresh plates become necessary. Edison nickel cells for traction service are supplied under a guarantee of full rated capacity at the end of four years' use, during which 45 000 to 60 000 miles may be run in commercial service. It should be remembered, however, that nickel

cells are generally between three and four times as dear as first-class lead traction cells in first cost, for the same effective kWh capacity. The four years' guarantee gives an element of security which should be particularly appreciated where service is heavy and annual mileage high, but, on the other hand, manufacturers of lead traction cells are prepared to enter into reasonable maintenance contracts on a mileage basis; so that, when choice of cell is permitted, decision should be reached by considering relative capital and annual costs for alternative equipments in the particular case concerned. The nickel cell will stand mechanical and electrical abuse which would ruin a lead cell; a user who has a maintenance contract for lead cells may not feel concerned about this difference, but the terms of the contract are naturally determined ultimately by the characteristics of the cell in service.

The general nature and action of lead traction cells are identical with those of lead-plate storage cells for stationary service (§ 431), but, to combine minimum weight with maximum strength, special mechanical arrangements have been devised for the lead skeleton and active material of the plates. These arrangements are such, also, as to render the active material specially accessible to the electrolyte and to electrolytic action. In the 'Ironclad-Exide' storage cell, for instance, the positive plates consist each of a number of vertical pencils carried between top and bottom horizontal bars. Each pencil has a leaden core covered with lead peroxide and surrounded by a hard rubber tube, which is slotted to permit access of electrolyte without permitting the escape of active material. The rubber sheathing allows for expansion and contraction of the active material, and is formed with projecting ribs which stiffen it and act as spacing pieces, so that only a plain wooden diaphragm is required between plates. The negative plates are of pasted construction, the active material being held in narrow grooves in a light but stiff casting. The low internal resistance of modern traction cells permits heavy charging or discharging currents without serious heating, and favours high Wh efficiency (§ 431).

The Edison cell (§ 434) uses nickel oxide and iron as its active materials, and a 21 % solution of caustic potash in water as electrolyte. There is practically no deterioration of the cell when standing idle or over-discharged, and in particular there is no sulphation (which is the great source of trouble in lead cells). All

the mechanical parts of the Edison cell are of steel. The positive plate consists of a number of tubes made by winding perforated nickel strip helically and securing it by steel rings; adjacent tubes are wound in opposite directions so that there may be no buckling. The tubes are held in a nickel-plated steel frame, and each tube is filled under pressure with alternate layers of flake nickel and nickel hydroxide. For the negative plates a mixture of iron oxide with a trace of mercury is pressed into corrugated and perforated steel pockets, which are then forced into a steel frame. An A-8 cell has eight positive plates measuring $4\frac{3}{4}$ in. by $9\frac{1}{4}$ in. each; whilst a B-6 cell has six plates, each $4\frac{3}{4}$ in. by $4\frac{5}{8}$ in., and so on. Plates of similar polarity are bolted together and to a terminal stem which passes through a special stuffing-box in the cover of the container. The latter is of corrugated steel plate, with welded joints, nickel-plated, and painted with insulating composition. Rubber separators are used between plates, and a filling vent with cap and gas vent is the only opening in the finished cell. During the first charge the green nickel hydroxide is converted to black nickel peroxide. Thereafter the cycle consists in oxidation of iron and reduction of NiO_2 to Ni_2O_3 on discharge; and in reduction of iron oxide and oxidation of Ni_2O_3 on charge.

The electrical characteristics of lead and nickel cells differ considerably (*see also* §§ 431, 434), and those of lead cells vary considerably according as the cells are built for stationary or traction service; lead cells for stationary service are dealt with in §§ 430 *et seq.* The higher efficiency of the lead cell and its higher voltage go a good way towards compensating for its heavier construction as compared with the nickel cell. A lead storage battery requires from 2.0 up to 2.6 V per cell during charging, and yields from 2.2 down to 1.85 V on discharge. A nickel battery, however, requires 1.55 to 1.85 V per cell for charging, and yields 1.35 to 1.05 V on discharge. The average voltage per cell during discharge may be taken as 2 V in lead, and 1.2 V in nickel batteries.* Due principally to its lower voltage per cell, a

* The Ah capacity of a traction-type storage cell is usually quoted at the 5-hr. rate. At this rate the permissible discharge current of a lead cell is about 1.7 times the 10-hr. discharge current, the Ah capacity is about 83 % of that on 10-hr. discharge and the permissible final voltage on discharge is about 1.81 V (*see* Fig. 155, § 431). The average voltage of the cell during such a discharge is about 1.92 V

nickel battery occupies more space than a lead battery for equal energy storage. A modern lead traction battery stores 1·5 to 2 kWh per cu. ft. of space occupied, whereas a nickel battery stores 1·2 to 1·3 kWh per cu. ft. A lead battery, however, stores only 8 to 10 Wh per lb. of cell (complete), whereas a nickel cell stores 12 to 14 Wh per lb. Reckoned on normal charge and discharge, the 'ampere-hour efficiency' ($= \text{Ah output} / \text{Ah input}$) is 85 to 90 % in lead and 75 to 80 % in nickel batteries; whilst the 'energy or watt-hour efficiency' ($= \text{Wh output} / \text{Wh input}$) is 70 to 80 % in lead and 55 to 60 % in nickel cells. Both ampere-hour and watt-hour efficiencies are considerably higher on rapidly alternating short-period charge and discharge, and this is of some interest in connection with boosting charges (§ 949) and regenerative braking (§ 900); but as a matter of fact the 20 % or so difference in watt-hour efficiencies between lead and nickel cells is not a vitally important consideration. The actual energy consumption of a battery vehicle is so low that even the 30 % higher input required, for equal kWh output, by a battery of 20 % lower Wh efficiency, does not represent a large addition to the running cost.

For example, a 300 Ah, 60 V battery may suffice for 40 miles' running of a 2-ton van. The total battery output is $300 \times 60 / 1\,000 = 18$ kWh, and this corresponds to an input of 22·5 kWh or 30 kWh, according as the watt-hour efficiency of the battery is 80 % or 60 %. The difference in favour of the more efficient battery is 7·5 kWh or (at 1d. a unit) $7\cdot5 / 40$, i.e. 0·19d. per mile. On a total of 8 000 miles per annum this represents £6 6s.—an appreciable sum, but not one of such magnitude as to decide alone the use of one type of battery in preference to the other.

Whereas 600 to 700 cycles of charge and discharge (corresponding, say, to two years' service and 16 000 to 20 000 miles' travel in delivery work) is about as much as one can count upon getting from a set of lead plates in traction batteries, the capacity being then reduced to about 80 % of its original value, a nickel cell has still its original capacity after 1 000 to 1 500 cycles of charge and discharge, and may be in service for from 6 or 8 years, during which period a distance of from 60 000 to 90 000 miles may be covered. So far as published data go at present, they appear to favour lead cells for use where mileages are moderate

(Fig. 154, § 431). If the average voltage per lead cell is to remain about 2 V for a period of 4 or 5 hours, the discharge current must not exceed that of the 10-hr. rate, as will be clear from Fig. 154.

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and low capital cost a consideration, and nickel cells for high annual mileages and for cases where the high initial investment can be afforded. In September, 1915, there were nearly 600 electrics in use or on order in Great Britain, and of these about 63 % had lead cells and 37 % nickel cells. By September, 1925, the number had risen to about 2 000 ; but it had fallen to 1 352 on September 30, 1931.*

940. Number of Cells ; Ampere-Hour Capacity.—Theoretically any number of cells could be used on a battery vehicle to provide the watt-hours storage capacity considered desirable. The total energy output available (in Wh) = battery output in Ah \times average total battery voltage. Using N cells, averaging 2 V (lead) or 1.2 V (nickel) each, the total battery voltage is $N \times 2$ V or $N \times 1.2$ V, so that, to maintain a certain watt-hour product, we may use N cells of a certain Ah capacity or $N / 2$ cells of twice that Ah capacity or $2 N$ cells of half the original Ah capacity, and so on. Carried to its limits, this means that we could use one very large cell, 50 medium-sized ones, or several hundred very small ones. Considerations of first cost, maintenance, size of wiring, efficient insulation, mechanical strength, and convenient size of cells determine the use of a medium number of reasonably large cells ; whilst consideration of convenience in recharging cells (§ 948) suggests that the maximum voltage required by the battery for charging should be about 110 V or 220 V, these being standard pressures for public electricity supply (§ 23). Practice varies somewhat among makers of lead-battery vehicles ; from 40 to 46 cells are used, but 42 cells may be taken as the most common allowance. Standard Edison vehicles employ 60 nickel cells. Small trucks and miscellaneous special types of vehicle employ other numbers of cells to suit individual circumstances, but general service electrics use batteries which are fairly well standardised at 42 lead or 60 nickel cells. These figures correspond to from 81 to 84 V mean discharge voltage for the lead battery and 72 V for the nickel battery (§ 939) ; the maximum charging pressure required across the battery itself is 110 V in both cases, but whereas the voltage of the lead cells does not fall more than about 10 % during the steady discharge period, that of nickel cells falls 15 to 20 % (i.e. from 78 V to 66 or 63 V).

* Full statistics of road vehicles are given in Ministry of Transport Report, No. 37A, 'Road Vehicles—Great Britain, 1932.' (H.M. Stationery Office.)

Just as the overall efficiency of petrol traction is expressed by the average petrol consumption per ton-mile, so is that of electric traction expressed by the watt-hours energy consumption per ton-mile. On good level roads and referred to the gross weight of vehicle, an average figure for a battery vehicle is 120 Wh battery output per ton-mile (§ 946). In other words, if

W = gross weight of the vehicle in tons,
 M = miles travelled per battery charge,
 N = number of cells in battery,
 V = mean discharge voltage per cell,
 C = ampere-hour output capacity of battery, and
 e = watt-hours battery output per ton-mile,

we have

$$e = (C \times N \times V) / (W \times M) \text{ Wh per ton mile.}$$

Hence the battery capacity $C = (e \times W \times M) / (N \times V)$ Ah. Assuming as an average value of e , 120 Wh per ton-mile (§ 946); and taking $V = 2.0$ V per cell for a lead battery and 1.2 V for a nickel cell; and allowing 42 cells in the lead, and 60 cells in the nickel battery, we have

Ah capacity of battery = $1.42 W \times M$, using lead cells,
 and = $1.67 W \times M$, using nickel cells.

The numerical coefficient in these equations varies with the actual energy consumption per ton-mile (§ 946); the values assumed for N and V are practically standard.

Table 201 shows the actual Ah capacity of batteries provided in

TABLE 201.—*Typical Ampere-hour Capacities of Electric Vehicle Batteries.*

Useful Load of Vehicle.	Lead Cells (4 to 5 Hour Rate).	Nickel Cells (all Practical Rates ; § 941).
$\frac{1}{2}$ ton	120-130 Ah	150-200 Ah
1 "	140-160	225-250
2 tons	170-220	300
3 "	200-250	375
4 "	250-300	450

a number of electrics now in service, and it is interesting to see how these data compare with results obtained from the above equations. In the case of a $\frac{1}{2}$ -ton van the gross weight may be 2 tons (Table 200), and the mileage per charge, 45 (Table 199), so that

a suitable battery capacity would seem to be $1.42 \times 2 \times 45 = 128$ Ah, using lead cells, or $1.67 \times 2 \times 45 = 150$ Ah, using nickel cells. In the case of a 3-ton wagon, the gross weight may be $2\frac{1}{4} \times 3$ or 6.75 tons (Table 200), and 35 miles per charge would be suitable (Table 199). On this basis the above formulæ suggest a lead battery of $1.42 \times 6.75 \times 35$ or 335 Ah, or a nickel battery of $1.67 \times 6.75 \times 35$, *i.e.* 395 Ah capacity. All of these results are in reasonably good agreement with Table 201.

941. Battery Capacity and Discharge Rate.—The ampere-hour capacity of any particular nickel cell is practically a physical constant of that cell (§ 434), but the quantity (Ah) of electricity which can safely be withdrawn from any lead cell depends a great deal on the rate of discharge (§ 431). It is frequently stated that a lead battery can be discharged safely to 1.85 V per cell, and that when this voltage is reached the battery is discharged. This is true only where comparatively slow discharge is concerned. If a lead cell be discharged very rapidly it may be taken down to 1.75 or 1.7 V per cell without injury, but the quantity of electricity which can be withdrawn during such a discharge may be half (or less) that obtainable during a slower discharge. It is neither desirable nor necessary to discharge a traction battery completely in 1 hour, but discharge often proceeds temporarily at that rate; hence it is important to remember (*a*) that the total output obtainable from a lead battery is reduced materially if the average current demanded is increased by reckless acceleration or by running over a hilly route; and (*b*) that the complete discharge of a nearly exhausted lead battery can often be postponed sufficiently to permit the vehicle to reach home, if speed and hence current consumption be reduced. Due partly to lower tractive resistance and partly to slower battery discharge, the vehicle mileage per charge is generally at least 10 % greater at 12 m.p.h. than at 15 m.p.h. Though the exact ratio varies with the make of cell, it may be taken that the 'safe' output of a lead battery, in terms of its Ah capacity on 10-hr. discharges, is 85 % at the 5-hr., 50 % at the 1-hr., and 35 % at the $\frac{1}{2}$ -hr. rate; the minimum permissible voltage in the four cases being 1.85, 1.83, 1.75, and 1.7 V per cell (*see* Fig. 155, § 431). The Ah capacity of lead traction batteries is usually stated on the basis of a 5-hr. discharge, this being approximately the quotient of (Mileage per charge / Average running speed in miles per hour).

942. Instruments on 'Electrics.'—The instruments which naturally suggest themselves for use on a battery vehicle are an ammeter, voltmeter, and ampere-hour meter. An ammeter is less useful than might be expected. It is, of course, important that excessive discharge current be avoided, but an indicating ammeter may not contribute much to this end. The voltage of a lead-type battery is an index to its state of discharge only 'if the rate of discharge be known (§ 941), and the same remark applies to the indications of an ampere-hour meter. For use with nickel cells, a reversible ampere-hour meter—fitted with a differential shunt or some other device, allowing for the fact that the total ampere-hour output is necessarily less than the input by an amount corresponding to the inefficiency of the battery (§ 939)—does give a fair representation of the state of discharge. For use with lead cells, an ingenious instrument has been devised by Rankin, and consists essentially of two moving-coil instruments within a single case. One of the moving-coil instruments is connected across a shunt in the battery cable, and thus deflects proportionately to the discharge current. This deflection is transferred through a special cam to a pointer which indicates the minimum permissible voltage per cell at the prevailing rate of discharge. The second moving-coil instrument is connected across the terminals of a section of the battery, and indicates the actual voltage per cell by means of a second pointer moving over the same scale as the first. When the position of the two pointers coincides, the actual cell voltage is the minimum permissible at the existing rate of discharge, and unless the rate of discharge can be reduced the battery must be considered discharged. In this instrument, as placed on the market for use in electric vehicles, the driver has indicated to him, by two pointers moving over a single scale, the total battery voltage, the actual voltage per cell, the permissible final voltage per cell, and the actual value of the current at each moment.

943. Motors for 'Electrics.'—Series-wound motors (§§ 676, 895) are generally employed in electrics, owing to their high starting torque and their valuable characteristic of slowing down automatically when loaded heavily (by weight, road surface, or gradient). Compound-wound motors (§ 677) are sometimes used, chiefly in conjunction with special field control (§ 945). A single motor is to be preferred on grounds of economy in space and

weight and in point of machine efficiency, but two motors are often used as an essential feature of the particular driving system employed (§ 944), or to suit some particular system of control (§ 945). The choice of motor speed and power is affected by the weight, speed, driving system, and wheel diameter of the vehicle. The rated motor voltage should be selected on the basis of 1.9 V per cell for lead batteries and 1.0 V per cell for nickel batteries; this leaves a sufficient margin to ensure that full terminal voltage is maintained on the motor during overload. The average efficiency of electric vehicle motors may be taken as 85 %, and the overall efficiency (battery output to road wheel) as 60 to 75 %, depending on the mechanical transmission employed (§ 944).

By comparison with the engine power usually provided in petrol vehicles, the motor power provided in electric vehicles may appear inadequate. It must be remembered, however, that the average power developed by a petrol engine during a day's run is much less than its nominal horse-power; but that the size of the engine is determined by the maximum power requirements, since a petrol engine has practically no overload capacity. On the other hand, a modern electric traction motor is capable of sustaining two or three times its rated load for half an hour or so, and may therefore be chosen to correspond closely with the average running-power requirements.

Suppose that a 60-cell nickel battery of 450 Ah capacity runs a 4-ton wagon 35 miles per charge at a constant speed of 7 m.p.h. (the maximum speed of which the vehicle is capable). The total energy output of the battery is $72 \text{ V} \times 450 \text{ Ah} = 32.4 \text{ kWh} = 43.5 \text{ H.P.-hrs.}$ The journey being accomplished in $35 / 7 = 5 \text{ hrs.}$, the mean power output of the battery (or input to the motor) is $43.5 / 5 = 8.7 \text{ H.P.}$ This figure is based on full-speed running on level road, and the motor actually provided might be a 6 H.P. machine capable of 15 H.P. for $\frac{1}{2}$ hr. or 1 hr. (Table 202). This example serves to show how very much below their rated power (and consequently below their maximum efficiency) petrol automobile engines must work (*see also* § 953). A 4-ton commercial chassis by a certain first-class firm is fitted with a 40 B.H.P. petrol engine, and this is quite typical.

Table 202 gives a general idea of the engine and motor power provided on petrol and electric commercial vehicles respectively, the data here given representing average modern practice. Single motors of fractional horse-power are fitted to small electric trucks and similar vehicles. On light vans two motors each of $1\frac{1}{2}$ or 2 H.P. (and capable of 2 to 3 times this output for $\frac{1}{2}$ hr. to 1 hr.) may be used, or a single motor of equivalent power may be

TABLE 202.—*Horse-power of Petrol and Electric Vehicles.*

Useful Load (Tons).	Horse-power of Motor.		
	In Petrol Vehicles.	In Electric Vehicles.	
		Rated.	Maximum (for $\frac{1}{2}$ to 1 hour).
$\frac{1}{2}$	15-20	2	6
1	25	3	8
2	30	4	10
3	35	5	12 $\frac{1}{2}$
4	40	6	15
5	40	7	17 $\frac{1}{2}$

employed. A certain make of electric landaulette uses two motors rated at 3 $\frac{1}{2}$ H.P. each. Heavy commercial vehicles use one or two motors totalling 15 to 20 H.P. (maximum). Naturally, the relatively low motor power limits the speed of electrics on hills, but in commercial service there is no particular advantage in gaining a few minutes on hill work—certainly none comparable with the merits of electric vehicles in other respects (§ 936).

944. Mechanical Arrangement of Drive.—It would be possible to install an electric motor in the position usually occupied by the engine of a petrol car and to retain all the mechanical features of the standard transmission of the latter. There is no need, however, for a clutch in an electric vehicle, and all desired speed changes can be effected more conveniently and efficiently by electrical means (§ 945) than by using a change-speed gear-box. Eliminating clutch and gear-box, we are left with a motor direct-coupled to a cardan shaft which drives the rear axle through a worm gear and differential or, alternatively, through bevel gearing. In a modification of this arrangement the motor (which may be near the front or the rear of the chassis) drives a countershaft instead of the road-wheel live-axle, and this countershaft is connected to the road wheels by side chains. So far, the motor axis has been supposed to lie along the centre line of the chassis. If the motor be placed across the frame, it may drive a countershaft through spur gearing or chain, transmission thence being by side chains as before. In the Cedes wheel all gears are eliminated. Two motor wheels (front or back) are used in each vehicle; the field system of each motor is mounted

on a stub axle, the armature is attached to the wheel rim, and a radial bar commutator is provided under an 'axle-cap' cover. It will be seen that this gearless system requires the motor to run at the same speed as the road wheel; to permit the use of a higher speed motor (which is lighter for equal power), simple spur gearing or 'sun-and-planet' gearing may be introduced between the motor spindle and road wheel, the motor still being mounted immediately alongside the wheel. It would hardly be fair to express preference for any one of these arrangements without going more fully into the matter than space permits. It is not difficult in any particular case to decide which transmission offers the best combination of efficiency with convenience of construction and operation. A countershaft and side-chain combination is very suitable for heavy commercial vehicles, so long as the chains be suitably enclosed and lubricated.

945. Speed Control and Braking.—A great advantage of the electric motor, as compared with the petrol engine, is that it yields practically constant power over a wide range of speed. Speed control in all battery vehicles is by changing the motor speed, and the latter in turn is controlled by changing the voltage applied to the armature, by varying the field strength, or by a combination of these methods. The switch-gear used to effect the desired changes in connections is generally built on the same lines as a tramway controller. It is very desirable that a master-switch be interlocked with the brake pedal so as to open the battery circuit when the brakes are applied; without this safeguard a careless driver may waste much energy, besides wearing the brakes rapidly and reducing their efficacy. When the battery circuit is thus opened, the controller should return automatically to the 'off' position, so that acceleration and current consumption may be graded properly on releasing the brakes and recommencing normal running. Methods of varying armature voltage include the use of variable external resistance in series with the armature; series-parallel control of battery sections, motors, or double-wound armature windings; or combinations of these methods. External resistance in series with the armature necessarily involves wastage of energy, hence this method of control should not be used where avoidable. Groups of cells connected in parallel are apt not to share the total load evenly (especially when the cells are nearly discharged), but, on the other hand, parallel connection of cells

reduces the current demanded from each group so connected, and therefore increases the total ampere-hours which can be withdrawn from a lead battery (§ 941). From 4 to 6 forward speeds—occasionally up to 10—are generally provided; the exact connections for each speed vary in different vehicles. The control system used with a pair of Cedes wheels (§ 944) is: (1) Motors in series with each other and with external resistance. (2) Motors in series. (3) Field windings in parallel, armatures in series. (4) Fields and armatures in parallel. A six-speed schedule (used in Krieger landaulettes) is: (1) Two battery halves in parallel, two compound motors in series. (2) Battery halves in parallel, motors as series machines in series (shunt fields cut out). (3) Batteries in series, motors in series as compound-wound machines. (4) Batteries in series, motors in series as series machines. (5) Batteries in series, motors paralleled as compound machines. (6) Batteries in series, motors in parallel as series machines. Where only a single motor is employed, control may be by series-parallel arrangement of battery in two sections and by use of resistance steps; by a similar arrangement supplemented by series-parallel manipulation of field-coil connections; or by resistance steps in the main circuit and series-parallel arrangement of the field coils, supplemented by arrangements for shunting the latter (the battery being in series all the time).

Luggage or goods trucks for use on platforms or in workshops, etc., are sometimes provided with as many reverse as forward speeds. Sometimes two, but generally only one, reverse speed is provided in road vehicles. Electro-dynamic braking is easily arranged for, and since the terminals of the motor (which then acts as generator) may be connected through the battery, the latter may be recharged to an appreciable extent during retardation periods or when running downhill. The total mileage obtainable per battery-charge is thus extended, and the total running costs are reduced by the saving effected in net current consumption. For electro-dynamic braking to be possible, the vehicle must of necessity be in motion; hence, to hold the car stationary and to act as reserve at other times, one or two mechanical brakes are necessary in addition to the braking notch on the controller.

Macfarlane-Burge Control System.—The object of this system is to protect the battery from excessive current demand and to reduce the dead-weight of the battery and other electrical

equipment. Use is made of a special rotary 'electric valve' and a special shunt-wound driving motor which has the characteristics of a series-wound motor (§§ 676, 895). The following notes are abridged from *Journal I.E.E.*, Vol. 49, p. 93 *et seq.* :—

Braking is entirely regenerative, the battery absorbing the energy returned. A high-efficiency rotary transformer or automatic electric valve transforms half the power supplied to the wheel motors and automatically limits the current that can be drawn from or returned to the battery; it displaces the usual series-parallel controller. The regenerative action of the driving motor comes into play whenever the driver reduces speed or stops the vehicle; in traffic, the battery operates under 'buffer' conditions (rapidly alternating charge and discharge) and therefore at high efficiency and with minimum depreciation. When starting or hill-climbing with the controller 'full on,' the torque is four times that on the level, with only $2\frac{1}{2}$ times normal current in the armature. The entire control is carried out by means of a pedal and a single reversing lever. The vehicle speed is adjusted automatically to the gradient of the road. Fewer battery cells are required, and these of reduced size and weight; the discharge rate being limited, the Ah-capacity is greater under working conditions (§ 941). It is not necessary to use two motors or a double commutator motor to obtain economical speed control. Energy, initial and upkeep costs are reduced, and the ratio of live to dead load is much increased. The control is so arranged that the motor can be made to give a small torque (negative or positive as required by the gradient) which 'holds' the vehicle electrically; ordinary electro-dynamic braking is only effective when the vehicle is in motion.

The system is of chief importance in connection with passenger buses and heavy commercial vehicles (*see also* § 953).

946. Energy Consumption of 'Electrics.'—So many factors affect the energy consumption of road vehicles that data relating thereto have little meaning unless qualified by a statement of conditions so lengthy or complex as to render comparisons between vehicles most difficult. It is a frequent experience that a vehicle which seems from a first inspection of its performance data to be very inefficient is actually found to be very economical when due allowance is made for road surface, gradient, wind pressure, and other influential factors. In an electric vehicle the basis to which energy consumption should be referred is the kWh-input to the battery, since this is what has to be paid for. It has been shown (§ 880) that the power required for uniform vehicle speed on the level can be referred to tractive resistance per ton weight moved. If the tractive resistance be r lb. per (gross) ton, the work done per ton-mile = $(5\ 280r)$ ft.-lb. = $(1.99r)$ Wh. Assuming 70 % overall efficiency for motor and transmission gear (§ 943), the motor input (*i.e.* the battery output, very nearly) = $1.99r / 0.7$ = $(2.85r)$ Wh per ton-mile. Taking the watt-hour efficiency of

lead and nickel cells to be 75 % and 55 %, respectively (§ 939), we find that the battery input required is about (3·8*r*) Wh per ton-mile with lead cells and (5·2*r*) Wh per ton-mile with nickel cells. The whole difficulty is to decide what is an average value for the coefficient *r* of tractive resistance.* Air resistance is not

* Reference may be made to a paper on the tractive resistance to an electric wagon equipped with solid rubber tyres and running on various urban roads at speeds up to 15½ m.p.h. (A. E. Kennelly and O. R. Schurig, *Am. I.E.E. Proc.*, Vol. 35, 1011-1039, June, 1916). Though the tests described are limited in scope, in that they relate to a single vehicle on urban roads and take no account of windage, they are very instructive. Some of the principal conclusions reached are : (1) Mechanical efficiency of transmission from motor shaft to rear wheel treads, through shaft drive and single-reduction worm gear, may be as high as 90 %. Under the most favourable conditions, the overall efficiency from battery terminals to rear wheel treads rose to 78 %. (2) Tractive resistances are most conveniently expressed as an equivalent percentage grade; e.g. a level road of tractive resistance *r* lb. per ton may be regarded as a road of zero tractive resistance, but rising uniformly *r* / 22·4 units in 100 units of road length, i.e. having an equivalent grade of *r* / 22·4 %. (Note.—A tractive resistance of 10 kg. per metric ton is equivalent to 1 % grade.) (3) Tractive resistance on level roads in the absence of wind is composed of displacement, impact, and air resistances. Displacement resistance varied in these tests from 0·85 % equivalent grade (19 lb. per ton) for hard smooth asphalt to 1·6 % (36 lb.) for a very soft tar macadam, and was practically constant for any given road. Impact resistance increases with speed (more rapidly on rougher roads), with road roughness, and with total weight of vehicle; it is negligible on good asphalt or other smooth pavement, and reaches its maximum value on badly worn macadam or granite-block roads with sand-filled joints. At 12·4 m.p.h. air resistance for the vehicle tested was 0·11 % equivalent grade (2½ lb. per ton), i.e. 4 % on the highest and 12·5 % on the lowest total tractive resistance. (4) The following urban pavements are enumerated in the order of their desirability from the point of view of low tractive resistance at 12½ m.p.h. The total tractive resistance increases nearly in direct proportion to the speed between the limits 10 and 15 m.p.h., and the figures bracketed below are the mean values obtained for total tractive resistance at 10 and 15 m.p.h. respectively, expressed in lb. per ton (of 2 240 lb.) and in percentage equivalent grade: Asphalt (21-23 lb., 0·93-1·08 % grade); wood block (24½-27½ lb., 1·1-1·24 % grade); hard, smooth macadam (23½-29½ lb., 1·06-1·32 % grade); brick block (25-31 lb., 1·13-1·38 % grade); granite block, cement-filled joints (26-36 lb., 1·17-1·62 % grade); cinder (28-35 lb., 1·25-1·56 % grade); gravel (31-37 lb., 1·38-1·65 % grade); granite block, sand-filled joints (40-58 lb., 1·83-2·6 % grade). (5) The tractive resistance of a badly worn macadam road may be three times that of a good asphalt road. Increasing the gross weight of the vehicle increases the tractive resistance on rough roads but not on smooth roads (within observed speed limits). A layer of dust 1 cm. (0·4 in.) thick adds about 3½ lb. (0·15 % equivalent grade) to the tractive resistance per ton at all speeds tested. (6) The total range of tractive resistance covered in these tests was from 21 lb. per ton (0·93 % equivalent grade) on best asphalt at lowest speed, to 60 lb. (2·7 % grade) on worst macadam at 12½ m.p.h. These results are reasonably consistent with the average figures stated in the text.

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a very important item till the speed with regard to the air reaches about 20 m.p.h., though of course the wind-catching surface of commercial vehicles is large. The influence of tyres and wheel diameter is appreciable, but the nature of the road surface is the most important factor. On hard, smooth asphalt the resistance to traction may be 30 lb. or less per ton; on granite setts, according to their smoothness and cleanliness, it may be anything from 30 up to 60 lb. per ton; the resistance offered by a macadam surface is very variable and may be lower than 40 lb., or, if the road be wet and cut up, the resistance may exceed 90 lb. per ton. Gradients at once add to or subtract from the effective tractive resistance at the rate of $22\frac{1}{2}$ lb. per 1 % slope. Probably 60 lb. per ton is as low a coefficient of tractive resistance as can be hoped for in average town and suburban service, and this, of course, is assuming level roads. On this basis the energy input required is $3.8 \times 60 = 230$ Wh per ton-mile with lead cells, and $5.2 \times 60 = 312$ Wh per ton-mile with nickel cells. These results, which represent no more than a general estimate on the bases assumed, may be compared with the data in Table 203, which is compiled from a number of sources;

TABLE 203.—*Approximate Energy Consumption of Electric Vehicles.*

Vehicle and Useful Load.	Battery Output—Wh per Gross ton-mile.	Battery Input—Wh per Gross ton-mile.	
		Lead Cells.	Nickel Cells.
2-passenger runabout	220-190 Wh	300-250 Wh	400-350 Wh
$\frac{1}{2}$ -ton van	210-190	280-250	380-350
1- to 2-ton van	165-135	220-180	300-250
3- to 5-ton wagons	130-110	170-150	240-210

since this table does not take specific account of the variables mentioned above, it must be accepted simply as a general indication of the energy consumption of electrics. Principally owing to the higher speed of lighter vehicles, the energy consumption of the latter per ton-mile is relatively high. By 'coasting' wherever possible, and by using the brakes as little as possible, a careful driver can effect considerable current economy. Due to the higher energy consumption per gross ton-mile, to the higher percentage of dead-weight, and to the greater annual mileage of light vans as

compared with heavy wagons, the annual energy consumption of the former is relatively greater. For instance, the annual current consumption per ton of useful load capacity may be 9 000 kWh in a $\frac{1}{2}$ -ton van, 3 500 kWh in a 2-ton van, and 2 000 kWh in a 5-ton vehicle.

947. Total Running Costs of 'Electrics.'—The total running cost of any automobile is a vexed question, due to differences in opinion as to what charges should be included. A mass of data has been published by the partisans of particular machines or equipment, without qualification as to the conditions to which the figures refer. With the best intent it is difficult to give costs which shall be generally acceptable, owing to the enormous influence of individual circumstances. It is believed, however, that Table 204 gives a reasonably fair statement of the costs of running

TABLE 204.—*Average Running Costs for Battery Vehicles.*

Pence Per Car-mile.	$\frac{1}{2}$ -1-ton Vans.	3-5-ton Wagons.
Interest, depreciation, and insurance	d. 2 to 2 $\frac{1}{2}$	d. 3 to 4
Current (at 1d. / kWh)	$\frac{1}{2}$ " $\frac{1}{2}$	1 " 1 $\frac{1}{2}$
Tyres	$\frac{1}{2}$ " $\frac{1}{2}$	$\frac{1}{2}$ " 1 $\frac{1}{2}$
Batteries	2 $\frac{1}{2}$ " 2 $\frac{3}{4}$	3 " 3 $\frac{1}{2}$
Repairs to chassis, etc.	$\frac{1}{2}$	1
Garage and wages (variable) . . .	3 " 4	4 " 4 $\frac{1}{2}$
Licence	$\frac{1}{2}$	$\frac{1}{2}$

a battery vehicle. Including standing charges, renewals costs, current supply, garage, and driver's wages (variable), the total cost per mile may be taken as 9d. to 11d. for $\frac{1}{2}$ - and 1-ton vans; 1s. for 2-ton wagons; and 1s. 2d. to 1s. 5d. for 3- to 5-ton wagons. A corresponding figure for an electric taxicab is 7d. or 8d. a mile. Arrangements can be made for both batteries and tyres to be kept in order under a maintenance contract (generally on a mileage basis); this is appreciated by users wishing to fix definitely their liability (*see also* § 950). Capital charges, garage, and wages average less per mile the greater the annual mileage of the vehicle.

948. Vehicle Battery Charging.—The remarks made in §§ 432, 434 concerning the care and charging of stationary lead accumulators are applicable to traction cells as well. The latter

are built to withstand heavy mechanical and electrical service; but it is still necessary to guard against excessive 'gassing'; to prevent the temperature of electrolyte rising above, say, 110° F.; and to guard against sulphation of plates by excessive discharge. The nickel cell cannot be injured by any overcharge or over-discharge likely to occur in practice, so long as the temperature of the electrolyte does not exceed, say, 115° F. Electric vehicle batteries may be charged on the user's premises or at garages or central stations. In either of the first two cases, private generating plant may be used or energy may be taken from central station mains. Except in large works, where use can be made of existing electrical equipment, it is generally cheaper to use central station supply (§ 950), which is also less liable to interruption by breakdown. Where vehicles run on definite routes or touch at definite points (*e.g.* depots, warehouses, etc.) in certain delivery areas, it is often convenient to install private charging plant so that a 'boosting' charge (§ 949) can be given during meal-times or loading periods, without losing any time or mileage. The cost of this equipment may legitimately be set against that of petrol storage tanks and pumps needed for a fleet of petrol vehicles. If used for battery charging alone, the generator may be a shunt-wound machine capable of voltage regulation between 90 and 110 V (for 44-cell lead or 60-cell nickel batteries); if the generator is to be used for general supply as well, a compound winding (§ 138) should be used, the series turns being short-circuited during battery charging. To meet the needs of owners who prefer to be relieved of all the responsibility of battery charging, and to meet the needs of commercial vehicles and pleasure cars, which have no fixed route and so are apt to require a boosting charge when away from their normal charging station, there are likely to spring up a series of 'electric' garages. There is no reason why existing garages should not take on this work. Already a number of central stations in this country have laid down charging plant for their own and public use (§ 950), and this practice is very much more common in the United States.

Most central stations in the United Kingdom give supply for lighting purposes at 200 to 220 V, and for power purposes at 400 to 500 V. The total energy required by a vehicle battery per charge is not large (say, 15 to 55 kWh), but the charging current may be anything from 20 A up to 100 A or 200 A during 'boosting'.

(§ 949); hence it is generally necessary to take current from the power mains. The maximum charging voltage required by a 44-cell lead battery is 115 V, and by a 60-cell nickel battery is 110 V, so that, even with 200 V supply, the use of resistance alone to absorb the excess voltage is very wasteful. Where only A.C. supply is available the use of a mercury-arc rectifier, a motor-generator, or a rotary converter is essential; and the cost of a motor-generator is almost invariably justified where the supply is D.C. The motor-generator may consist of two mechanically coupled but electrically independent machines, the motor connected across the supply mains and the generator (with variable shunt-field) feeding the battery. Alternatively, the motor and generator armatures may be connected in series across the supply mains, the motor-field and variable generator-field being connected in parallel across the mains and the battery connected across the generator terminals. This arrangement, which is that of the 'Lancashire' reducer-set, gives from 4 to 12 % higher efficiency of conversion as compared with an ordinary motor-generator. Where a number of vehicle batteries have to be charged simultaneously, a 5-wire balancer may be used. As long as the load is divided uniformly, the balancer runs light across the 440 V mains; and when the load is not divided evenly, the balancer supplies the out-of-balance current needed to maintain 110 V across each section of the 5-wire circuit.

The fact that there are no 'end-cells' (§ 432) in a traction battery greatly simplifies its charging. The battery voltage falls 10 % with lead cells, or 15 to 20 % with nickel cells (§ 936) during discharge, and every cell then needs (normally) the same treatment during charging.

(1) *Charging at Constant Current.*—If the battery is to be charged by the so-called constant-current method ordinarily used for stationary batteries, the applied voltage must be increased from about 2.2 V per lead cell (1.55 V per nickel cell) at the beginning of the charge to 2.6 and 1.85 V respectively at the end of the charge. This adjustment of voltage involves continual attendance during the charging period. By the use of series resistance, batteries of different voltage can be charged from the same supply, but the series resistance will have to be adjusted as the charge proceeds. A lead traction-type cell is usually charged, under these conditions, at a current which is initially about 80 % of its normal discharge current (5-hr. rate), which tails off to about 33 % of the

same during the final stages of the charge. The normal charging current of a nickel cell for 7 hrs. is the same as the normal discharge current at the 5-hr. rate.

(2) *Charging at Constant Voltage.*—Due to their special construction, traction cells are able to stand much heavier charging currents (§ 949) than cells of similar capacity built for stationary service, so long as the temperature of the electrolyte does not exceed the limits already specified. The current may be particularly heavy during the initial stages of charging, and this makes possible *constant-voltage charging*, in which the battery is connected directly to a source of D.C. supply of voltage equivalent to 2·3 V per cell, *i.e.* 100 V for a 44-cell lead battery, or 1·67 V per cell, *i.e.* 100 V for a 60-cell nickel battery. The current flowing at first is very heavy, but as the back-E.M.F. of the cells rises, the net forward-E.M.F. diminishes automatically, and the current is consequently reduced. Using this method, it is impossible to injure cells by carelessness or ignorance. Naturally, charging proceeds quite slowly when the back-E.M.F. of the cells approaches the figure on which the charging voltage is based, and it is impossible to give quite so full a charge as when the charging voltage is raised to 2·6 V (lead) or 1·85 V (nickel) per cell. Since, however, the voltage of a lead cell falls to 2·2 V and of a nickel cell to 1·3 V at a very early stage in discharge, it is possible to utilise practically the full capacity of cells by the constant-voltage charging system. The constant-voltage system is the quickest method of charging, practically the full capacity of the cells being reached in about 5 hours. Owing to the influence of the variations in voltage on the charging rate, it is necessary to maintain very close regulation of voltage; and it is only possible to charge batteries of the same voltage from the same bus-bars. The current rush during the beginning of the charge is so heavy that, if a number of batteries have to be charged, they should be switched in one at a time, at intervals of, say, 15 minutes.

(3) *Modified Constant-Voltage System.*—In this system of charging, a constant voltage of about 2·5 V per lead cell, or 1·85 V per nickel cell, is maintained at the bus-bars, and a fixed ballast resistance (with positive temperature coefficient) is placed in series with each battery. During the first stages of the charge, when the current is heavy, the IR drop in the ballast resistance reduces P.D. across the battery to about 2·3 V per lead cell or 1·67 V per

nickel cell. As the charge proceeds, the current drops with the rising counter E.M.F.; and therefore the IR drop in the fixed resistance decreases, both on this account and because of its lowered resistance with lowered temperature, so that the P.D. across the battery rises until there is finally available practically the full bus-bar voltage on the cells. Charging is therefore 'finished' more completely than by the ordinary constant-voltage system.

949. Boosting Vehicle Batteries.—Normally the battery of an electric vehicle will be recharged during the 8 or 10 night-hours when it is standing idle in garage, but the mileage per charge of a reasonably light battery is limited (Table 199, § 937), and is often insufficient for the distance which the vehicle is otherwise capable of travelling in the service to which it is applied. This limitation may be removed by keeping fully charged batteries ready for exchange with exhausted batteries, but this method is impracticable until electric vehicles become much more common than at present. Under existing conditions it is simpler and more economical to arrange for boosting charges, *i.e.* partial charges at heavy current, to be given to cells at the termini on bus routes, at loading points, or during meal times in industrial service, or at central station or other garages. Nickel cells can safely be charged at five times the normal rate for 5 or 10 minutes or at twice the normal rate for an hour, and certain types of lead traction cells are able to withstand practically the same treatment without injury. According to the state of discharge of the battery, a one hour's boost will add anything up to 50 % to the daily mileage possible without actual exchange of cells.

950. Facilities and Tariffs for Vehicle Battery Charging.—The extended use of electric battery vehicles for commercial service and for suitable classes of pleasure service depends very largely on current being available quickly, at reasonable prices, and within a reasonable distance whenever required for battery charging. Whatever the locality, it is not difficult to arrange for the normal, complete charge each night, but before electric vehicles can become anything like so numerous as petrol vehicles it is necessary that there be a network of boosting stations and/or stations where exhausted batteries can be exchanged for fully charged ones. The ultimate solution probably lies in the establishment of electric garages all over the country, but the first step lies with existing central stations. There the necessary energy is already permanently

available, and it only remains to install suitable pressure-reducing apparatus in a conveniently situated charging station. Night-charging load is one of the most favourable the central station could wish for, to improve its load factor (§§ 259 *et seq.*); boosting charges are less favourable, since they demand a heavy current for a short time, but their effect is not at all serious where an industrial supply station is concerned, and the demand is entirely off the 'peak' of a station chiefly for lighting; most commercial vehicles are boosted during the dinner-hour, when other industrial demands are low. The Electric Vehicle Committee of the I.M.E.A. has recommended that the tariff for electric vehicle battery charging should not exceed 1d. per unit for off-peak supply, the minimum charge for current taken at any one time to be not less than 2s. There are already about 130 central station districts in the United Kingdom in which the tariff for charging vehicle batteries is from 1d. to 2d. per kWh; even a considerably higher tariff would not make the electric vehicle unduly expensive because the energy consumed represents (at 1d. / kWh) only 5 to 10 % of the total running costs (Table 204, § 947). Commercial electric vehicles are distinctly worth encouraging from the central station point of view, for each represents a potential consumer of current to the value of from £20 to £50 or more per annum (at 1d. a unit), according to its size and duty. Whereas the cost of electrical energy decreases steadily from year to year, that of petrol will probably continue to rise, if only by taxation.

The battery is the only part of an electric vehicle needing any skilled attention, and it is most probable that arrangements will gradually be made (in large towns, if not all over the country) to relieve the users of these vehicles of all responsibility for charging and maintaining batteries, by simply giving them a fully charged battery in exchange for an exhausted one whenever required. This is only carrying the principle of battery maintenance contracts one step further, but it requires a considerable number of electricians to be in use before it becomes practicable. A certain American company, which has organised a service on this basis, charges so much per month for garage (including cleaning, lubricating, and minor adjustments), so much for battery service (including charging and maintenance), and an additional charge per mile as recorded by a milometer on the vehicle. Assuming the average mileages stated, these charges work out as follows (*cf.* § 947):—

Useful load of vehicle . . .	$\frac{1}{2}$ ton	2 tons	5 tons
Average miles per month . .	830	750	580
Charge per mile—garage service	1.15d.	1.27d.	2.24d.
" " battery service	1.02d.	1.87d.	3.08d.
" " mileage charge	1.13d.	2.25d.	3.25d.
total	3.8d.	5.4d.	8.6d.

Capital, depreciation, and insurance charges, maintenance of tyres and chassis, and driver's wages are in addition to the above, and have to be taken into account by the user on his own responsibility.

951. Industrial Trucks and Tractors.—Self-propelling battery-type trucks and tractors are now used in large numbers and great variety, for carrying or pulling loads in and about industrial establishments, railway stations, wharves and other places. For general service, and for loads up to 2 tons, the trucks are usually on wheels with solid rubber tyres; for heavier loads, up to 30 tons or so, similar trucks are made to run on rails.

A special feature of the smaller trucks is their mobility and flexibility; a 2-ton truck, which can be turned on a radius of 6 to 8 ft., has a platform from 6 to 8 by 4 ft. and a track width of $2\frac{1}{2}$ to $3\frac{1}{2}$ ft., and can be used in almost any workshop. If desired, the truck can be arranged to run under and pick up loading-trays, which it can then transport to the desired place, dumping them there and going on to the next job; a truck of this type is never idle for loading or unloading. A series motor of from $1\frac{1}{2}$ to $2\frac{1}{2}$ h.p. is generally employed, with a controller giving two or three forward, and the same number of reverse, speeds, up to 6 or 8 m.p.h.; from 12 to 20 lead cells, or 20 to 30 nickel cells, of from 150 to 250 Ah capacity (5-hr. rate) are usually provided; and the dead-weight of a 2-ton truck is from 1 to $1\frac{1}{2}$ tons according to the type and size of platform fitted. Such a truck will haul a 2-ton trailer on the level. A runabout crane, mounted on a battery truck, and driven from the same battery, is also useful. In all trucks of these types it is usual for the driver to stand on a low platform at one end, facing in either direction, and to steer with one hand while manipulating the controller with the other; a pedal must be depressed to close the main switch and release the brake.

The battery of an industrial truck can be used to operate a motor for any temporary power service where no regular service is available (*e.g.* Fig. 394, § 850). Conversely, a portable petrol-electric generating set, on a lorry, can be used to re-charge the batteries of trucks which are employed temporarily, where there are no other charging facilities.

Battery-type electric tractors for use in marshalling railway trucks, or in other low-speed, short-distance haulage service, consist of a storage battery and driving motor mounted on a truck which may have either one or two axles, with wheels for use either on rails or on the ground or floor. The single-axle tractor has small

bearer wheels at each end of the frame to support the latter when the tractor is at rest; the drive, however, is through the main wheels on the central axle, the truck being balanced with regard to the axle so that one man can hold the truck level (with its bearer wheels on the ground) and guide it as desired. When the tractor is in use, its whole weight is on the two driving wheels, which usually have solid rubber tyres. A tractor of this type, with a 40-cell lead battery and a $3\frac{1}{2}$ h.p. motor, weighs about $1\frac{1}{2}$ tons and, exerting a pull of 550 lb., is capable of hauling 50 tons on level rails at $2\frac{1}{2}$ m.p.h.; the driver walks with the tractor, steering it with one hand and manipulating a controller wheel with the other. For use on rails, four-wheeled tractors are made, the driver then riding on the tractor. Such tractors are simple electric locomotives; weighing from $2\frac{1}{2}$ to 4 tons, they will haul from 50 to 100 tons at $2\frac{1}{2}$ m.p.h. on the level. The drive may be by a 10-h.p. motor geared to one axle, the two axles being chain-coupled so that the whole weight is on the driving wheels. If the truck be low and short, it can go on a turn-table with a railway wagon; on the other hand, if it be made longer and with a flat platform, it can be used for carrying heavy loads (§ 832).

952. Standard Charging Plugs and Sockets.—Wherever a battery is to be charged without removal from its vehicle, a plug-socket is provided so that connection can be made quickly to the battery by a plug and a flexible cable from the motor-generator or other charging apparatus (§ 948). It is obviously of the utmost importance that the dimensions of these plugs and sockets be standardised, otherwise much unnecessary expense and inconvenience would be caused in charging stations. The Electric Vehicle Association of America has standardised 50 A and 150 A charging plugs and receptacles, and in this country the British Standards Institution has standardised, in B.S.I. Report No. 74, the leading dimensions for a standard concentric plug and socket to be used on circuits up to 250 V, and for currents not exceeding 150 A continuously or 200 A for 1 hour. The shells of both plug and socket are to be solid-drawn mild steel or bronze tubing; and the main contacts of gun-metal, with lug connections for cables. It is further specified that a contact be provided to connect the shells of socket and plug, the latter being fitted with a lug for a 7/0·064 in. earthing cable.

953. Petrol-Electric Vehicles.—Under this heading may fairly be classed any vehicle in which thermal energy stored in petrol is converted to mechanical energy by a petrol engine, the mechanical energy produced being converted to electrical energy and back again to mechanical energy by a dynamo and electric motor. The justification for this apparently needless double conversion lies in substituting the efficiency of electric transmission, the flexibility of electric control, the excellent torque, speed, and

overload characteristics of the electric motor, for the lower efficiency and marked inflexibility of mechanical transmission, and the poor traction characteristics of the petrol motor. The system is used mainly for the heavier classes of vehicle, especially motor buses and lorries; but the advantages are such that it may also be used for private cars. It has been demonstrated that, without throttling the engine, a car of this type can be made to crawl at a barely perceptible speed; and that the high torque enables it literally to creep up the steepest pitch, such as a high vertical curb-stone. The petrol-electric systems described below are representative.

Tilling-Stevens System.—In this system the flywheel, clutch, and gear-box of an ordinary petrol vehicle are replaced by a dynamo, controller, and series motor, the latter being direct-coupled to a cardan shaft driving the rear axle in the usual manner. The electrical circuit is not broken whilst driving, all control being by the engine throttle supplemented by a forward-neutral-reverse switch and a field switch for use on hills. About 85 % of the engine output reaches the motor, and 70 to 75 % reaches the road wheels. The dynamo is so wound and designed that its E.M.F. falls automatically when the engine would otherwise be overloaded by the current demanded. In other words, the speed of the vehicle is controlled by the engine throttle till the engine is fully loaded, after which the speed falls automatically without affecting the engine. A shunt resistance is provided by which the generator field can be varied to permit increased engine speed on stiff gradients. The average engine speed is considerably lower than that of the cardan shaft. The details of the electrical equipment are such that neither engine, motor, nor tyres can be subjected to shock or excessive acceleration. No battery has to be carried; it is claimed that the engine and dynamo which replace it yield greater power than a battery four times their weight, and there is, of course, no such limitation of mileage as that imposed by the necessity for recharging a battery vehicle. A Tilling-Stevens six-wheeled petrol-electric was put on the market in 1927, the chassis weighing 5 tons and costing £1 750 (*Times Rev.*, 1928).

The Thomas Transmission.—The distinctive feature of this system is that it gives a direct mechanical drive on top speed, and at all other speeds transmits part of the power mechanically and the rest electrically. Any desired number of speeds can be provided by simple additions to the single-lever controller employed. The only battery carried consists of a few cells for lighting purposes and to start the engine; these cells are kept charged automatically. The equipment consists of a petrol engine driving a hollow cylindrical casing within which is a double 'sun-and-planet' gear. The two sets of wheels in the latter drive concentric shafts, each carrying the armature of one of two similar electrical machines. The inner shaft is also connected to the propeller shaft of the car. The double sun-and-planet gear gives a differential motion to the two shafts, the speed ratio being determined by their relative resistances to motion, and this again by field-control of the power transmitted electrically from one machine to the other. The armatures of the two machines are connected in series; one acts as a motor and the other as a dynamo, their functions being reversed at a certain speed. Speed control is obtained by an oil-immersed controller regulating the fields of the two electrical machines, but at full speed all power is transmitted mechanically to the propeller shaft.

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Macfarlane-Burge System.—This is a modification of the all-electric system mentioned in § 945. A petrol engine is used, of sufficient power to supply the average requirements for propulsion (§ 943), and this is supplemented by a small battery of about one-fifth the capacity required in the all-electric system, this battery being again protected against excessive currents by the rotary, automatic 'electric valve' (§ 945). The engine is coupled to the electric valve, between which and the driving motor purely electric transmission is used. The engine takes the average load, and the battery supplies peak demands and absorbs energy returned during regenerative braking. In addition, the battery is used for lighting and to start the engine, and also permits of electric braking down to any speed. The following notes are instructive :—

To drive a 6-ton (loaded) vehicle on the level at 12 m.p.h. requires 9 B.H.P.* When running at half-speed uphill, the M.-B. equipment changes the gear ratio automatically and permits the full 9 H.P. to be utilised, the torque being then twice that on the level. By the aid of the battery, the motors are enabled to develop an additional 9 H.P., making a total of four times the normal torque. On the other hand, a petrol vehicle running up the same hill at half-speed on top gear would need a 36 H.P. engine (to develop 18 H.P. at half-speed). Earlier change of gear would permit a smaller engine to be used, but there are loss of compression and decreased carburettor efficiency to be taken into account, and it is a fact that 36 to 40 H.P. water-cooled engines are actually fitted to such vehicles (§ 943). The M.-B. system requires only a 9 H.P. air-cooled engine and a battery capable of yielding 50 Ah on the 1-hr. rate. (*Jour. I.E.E.*, Vol. 49, 109, abridged.)

954. Trolley Buses or Trackless-Trolley Vehicles.—The trolley bus is simply a trolley-tramcar running on the ordinary road surface instead of on rails. It is given the general form, outward appearance, and rubber-tyred wheels of a petrol motor bus, and may be either a single- or a double-deck vehicle. It has two trolley arms (standard British practice) or else towing and conductor cables leading to a little truck running on the two overhead lines. It was formerly considered that where the vehicle ran over trolley tram routes it need use only one overhead line if a boom and skate or brush were mounted under the chassis to connect with the rails as return path for current. The use of the rail return, where available, saves the cost of a negative overhead line, but at the expense of a serious sacrifice of traffic flexibility, and the authors are unaware of any system now using skates.

Trackless trolley vehicles are limited to public passenger service and to goods-transport service in conjunction therewith. They were originally regarded as useful for opening out districts in which the capital cost of a trolley tramway was unjustifiable,

* This is the theoretical power required, assuming 100 % efficiency and a tractive resistance of 47 lb. per ton, which is low (§ 946). The main points illustrated by the example are not affected by this.

but trackless trolley buses have proved so satisfactory in service that they are being substituted for electric tramways in places where the existing rails are worn out—for the replacement of the rails is one of the most expensive items of maintenance, and was always under-estimated for in early days. It has been demonstrated repeatedly that trolley buses are more economical than petrol buses as regards power and repair costs; the higher first cost occasioned by the trolley wires and feeders is sometimes a serious consideration, but this need not be so if the feeders are part of the general electrical development of the district. The collector gear of the ordinary underhung-trolley type has been improved to such an extent that the trackless car can safely manoeuvre at full speed over a 30-ft. road, and at lower speed over 40 ft.

The electrical features of the early trolley buses were closely similar to those of tramcars, two motors, each of 15-25 H.P., being used, with series-parallel control. Modern practice, however, is to use a single motor of 80 or even 90 H.P. (1-hr. rating) with diverter field control and, in some instances, provision for regenerative braking. This arrangement is simpler, and costs less initially and in maintenance, than two motors with series-parallel control; and the design of the single motor is such that most of the required speed control can be effected efficiently by field variation.

A 74-seat double-deck trolley bus put in service by the London United Tramways in 1933 (*Tram. and Rly. Wld.*, Vol. 73, p. 111), measures 29½ ft. in overall length and weighs under 13 tons fully laden. A single motor is used, rated at 80 H.P. (1-hr. rating), 500 V; gear ratio 9·33; armature r.p.m. = M.P.H. × 80·8. This is a series-wound machine with field-control. A foot-operated master controller actuates the control contactors. Low-pressure tyres are used on all six wheels; and pneumatically-operated double sliding centre doors are interlocked with the driving circuit.

It is possible that battery buses will be used in preference to trolley buses for 'development' or 'feeder' work in future, since they involve no capital outlay beyond the cost of the vehicles themselves, and perhaps a boosting set at the inner terminus of each route. Another possibility, which is already being utilised, is that of adding a storage battery to a trackless trolley vehicle, so that the latter can run beyond, or digress from, the trolley-wire route; this is particularly useful in the case of goods-carrying vehicles. Alternatively, a petrol-electric engine and generator may be provided for use when the vehicle leaves the trolley wires. Trailers have been used on trackless buses in South Africa, and their use is likely to spread in the Dominions.

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Descriptions of particular systems have appeared from time to time in the technical Press; and reference may be made to a paper by C. W. J. Taffs,* which is particularly valuable in that it contains detailed comparisons between the costs of tramways, motor omnibuses and trolley buses, so arranged that the author's figures can easily be modified to suit different basic conditions.

The data in Table 205 may be useful for the purposes of general

TABLE 205.—*Comparison between Tramways, Motor Buses, and Railless Trolley Vehicles.*

	Tramway and Tramcar.	Motor Bus.	Trolley Bus.
Seating capacity (limited by permissible axle load)	Up to 85	Up to 66	Up to 66 (74 experi- mental)
Unladen weight per seat:			484 lb.†
Single-deck (s.d.) . .	896 lb.	480 lb.†	
Double-deck (d.d.), 4- wheel	420-500 lb.	255 lb.†	277 lb.†
Double deck, 6-wheel . .	—	280 lb.†	310 lb.†
Energy used per car-mile‡		<i>Petrol.</i> <i>Diesel.</i>	
Minimum	0.77 kWh	0.11 gal. 0.085 gal.	1.29 kWh
L.C.C. Tramways . .	2.74 kWh	—	—
Maximum	3.38 kWh	0.34 gal. 0.17 gal.	2.30 kWh
Average	2.27 kWh	0.2 gal. 0.11 gal.	1.78 kWh
Cost of average energy per car-mile (at $\frac{3}{4}$ d. / kWh, 1s. 8d. / gal. petrol, $4\frac{1}{4}$ d. / gal. Diesel oil)	1.7d.	3d. 0.5d.	1.33d.
Cost of vehicle (approx.) .	£2 000	£1 300 s.d. £1 700 d.d.	£1 400 s.d. £2 000 d.d.
Cost of overhead equip- ment per mile :			
2-wire—tramway	£3 000	—	—
4-wire—railless	—	—	£4 000
Cost of double tramway track per mile	£25 000	—	—

estimates. Comparisons between the energy consumptions and costs of tramcars, motor buses and trolley buses are interesting but by no means decisive. Wages cost much more than power; debt charges are important; repairs and maintenance costs are very

* Paper on 'Railless Trolley Traction,' by C. W. J. Taffs, before Inst. of Automobile Engineers, 1923; see *El. Rev.*, Vol. 92, p. 193.

† The Ministry of Transport fixes the maximum laden weight of buses: s.d., 9 tons; d.d., 4-wheel, 10 tons (10½ tons for trolley bus with all low-pressure tyres); d.d., 6-wheel, 12 tons (13 tons for trolley bus with all low-pressure tyres).

‡ Based on 1931-32 M.O.T. returns for England, Wales and Scotland, as regards trams and trolley buses.

different for the three classes of vehicles. For instance, the power cost of a tramcar is only about 15 % of the total cost of operation, including capital charges; and the useful life of a tramcar is 20-30 years, compared with 5 years for a motor bus.

By the courtesy of Mr. C. Owen Silvers, General Manager and Engineer of the Wolverhampton Corporation Transport Department, the authors are able to present the data in Table 205A, giving a

TABLE 205A.—*Working Costs of Tramways, Motor Buses and Railless Trolley Vehicles (Wolverhampton).*

Year.	Working Costs, in Pence per Vehicle Mile.			Working Costs, in Pence per 100-Seat Mile.		
	Trolley Vehicles.	Motor Omnibuses.	Tramways.	Trolley Vehicles.	Motor Omnibuses.	Tramways.
1925	11·084	11·721	13·571	29·82	36·62	29·50
1926	11·006	12·215	13·646	29·745	38·171	29·746
1927	11·457	12·257	13·888	30·15	35·02	24·579
1928	10·968	11·981	13·027	24·373	33·280	28·568
1929	10·877	12·132	14·570	23·142	29·590	—
1930	10·380	12·299	—	21·183	29·997	—
1931	10·335	11·788	—	20·67	29·47	—
1932	10·343	11·011	—	20·686	26·216	—

comparative statement of costs on the Wolverhampton system for tramways, motor omnibuses and railless trolley vehicles over a period of years; the operating costs are given per vehicle mile and per 100-seat mile.

With the warning 'there are no two undertakings sufficiently similar in essential conditions to render them truly comparable,' Mr. C. R. Tattam* gives the following operating costs of the trams, trolley buses and petrol buses in Bradford for the year ending March, 31, 1933 :—

	Tramcars.	Trolley Buses.	Petrol
Average seats per vehicle	55·6	42·1	39·1
Total miles run	6 230 245	2 001 534	2 578 602
Operating costs per 100-seat miles	24·018d.	28·943d.	29·349d.

The average costs of electricity and petrol were 0·886d. / kWh and 11·88d. / gal. respectively. A substantial proportion of the trolley buses date back to 1926.

* 'Tramcars, Trolley Buses and Petrol Buses,' Municipal Tramways and Transport Association, 1933. *Tram. and Rly. Wld.*, July, 1933.

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The comparative merits of the various systems depend considerably on the density of the traffic and consequent headway of the cars.* In this connection Mr. R. H. Wilkinson has stated that the critical point, where the single-line tramway and the trackless bus are on all fours, lies near a 3-minute service; and that, with a 2-minute headway, trackless traction is more economical than a double-line but more costly than a single-line tramway.† As the headway increases, the petrol motor bus, having no other standing capital charges than those on its own cost, becomes a more formidable competitor in the race; and when the headway exceeds about 30 mins. the railless vehicle can no longer hold its own. The higher and smoother acceleration which both electric vehicles have, in comparison with motor buses, is an advantage which cannot be gainsaid, especially where stops are frequent; and both also have the enormous temporary overload capacity common to all electric motors. This is required on steep gradients, and is conspicuously lacking in petrol engines, which must be designed for the maximum effort required of them.

The following comparisons, based on statistics published by the Ministry of Transport, show the rapid increase in popularity of trolley buses in this country:—

Year.	Route Miles Operated.	No. of Vehicles.	Car Miles.	Carried.
1921-22	47	80	1 374 444	9 879 730
1931-32	256	691	19 739 000	184 373 190

The weight of the electric motors now used is about 12 lb. / H.P., and those rated at 80 H.P. are capable of developing 160 H.P. for short periods. Maintenance costs of trolley buses are lower than those of petrol buses working under similar circumstances.

955. Bibliography.—(See explanatory note, § 58, Vol. 1.)

REGULATIONS, ETC.

Regulations and Bye-laws made by the Minister of Transport as regards electrical power on individual systems (§ 1052, Ch. 41). See, for example, Statutory Rules and Orders, 1920, Nos. 671, 672. (H.M. Stationery Office.) See also Chapter 41 generally and, in particular, § 1052.

Tramways and Light Railways and Trackless Trolley Undertakings: Statistical Returns. (H.M. Stationery Office.)

* For an analysis of the relative merits of tramways, trolley buses and petrol buses, operating and maintenance data, under American conditions, see 'Ideal Transportation System for Cities of Various Sizes,' by J. C. Thirlwall, *Gen. El. Rev.*, Vol. 34, p. 192.

† *El. Rev.*, Vol. 91, p. 9.

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MISCELLANEOUS.

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 Constant-potential System of Accumulator Charging. *El. Rev.*, Vol. 102, p. 95.
The Electric Vehicle (monthly). Official organ of the Electric Vehicle Committee of Great Britain.
The Tramway and Railway World, which also publishes annual analyses of tramway and trolley bus costs, and *The Electric Railway, Bus and Tram Journal* should be consulted for new developments. *See also* Bibliography § 934.

CHAPTER 37.

ELECTRICAL PROPULSION OF SHIPS AND THE DRIVING OF AUXILIARIES.

956. Introductory.—This volume would be incomplete without brief reference to modern tendencies in shipbuilding, as modified by the progress of electrical science; but space does not permit of more than a cursory outline of what may hereafter be of paramount importance both in peace and war.

The first application of electricity on shipboard was for internal lighting, where success was assured from the outset because it solved the problem of fumes from the combustion of candles and oil. Searchlights—originally for use in the Suez Canal—followed, together with flood-lighting for cargo work. Once generating plant was regularly installed the electrical driving of various auxiliary machines (§ 964) inevitably began to exert its claim, until it became almost universal; though for a long time it was held inadvisable to trust electricity for certain operations where any failure at a critical moment would spell disaster. That stage is long passed.

As the agent for actual electrical propulsion, D.C. motors driven by batteries were early in the field for small river craft; hundreds of these were working in the nineteenth century. As in the case of electric road vehicles (Chap. 36), no organised endeavour has ever been made in this country to facilitate 'off-peak' charging of batteries at low rates, and this branch has not made further headway.

Without attempting to give an historical outline of the development of electric ship propulsion* it deserves to be stated that twenty-five years ago Capt. Durnall† described an equipment

* Such an outline, from the American standpoint mainly, is given in 'Historical Review of Electrical Applications on Shipboard,' by H. L. Hibbard and W. Hetherington. *Jour. Amer. I.E.E.*, March, 1925, p. 249.

† Paper read before the Institute of Marine Engineers, 'The Generation and Electrical Transmission of Power for Main Marine Propulsion and Speed Regulation,' July, 1908 (*Proc.*, Vol. 20).

essentially similar to that used in the latest electrically driven ships, and foretold accurately the important advantages to be realised from the method. Many prejudices had to be overcome, however,—an eminent authority even suggesting possible asphyxiation of crews by copper fumes from short-circuits!—and it was left to the United States Navy to make the first large-scale applications of the system. Lloyd's Register for 1927-28 mentions 48 vessels, aggregating 137 000 tons displacement, electrically propelled; while on June 30, 1932, there were 48 vessels of 116 684 gross tons with Diesel-electric, and 42 vessels of 388 962 gross tons with turbo-electric propulsion, a total of 90 vessels and 505 646 tons.

In an article on the same subject as this chapter,* the economic conditions of the problem are discussed as regards both steamships and motor ships, embracing at present mechanical driving by (1) reciprocating engines; (2) the same with exhaust turbines; (3) low-speed turbines; (4) high-speed turbines and gearing; (5) low-speed Diesels; (6) high-speed Diesels and gearing. After pointing out that the electrical equivalent of a geared mechanical drive has no inherent and outstanding advantage over the latter in size, weight, efficiency or operation (though in this last item we do not agree with him) the author of the paper goes on to point out that the chief claim of electricity lies in the immense and growing modern importance of the auxiliary power requirements (§ 964 and throughout this chapter), which are every day becoming more complex and more essential both in passenger and cargo ships; so much so that main electric driving can be justified by this alone when the ratio of auxiliary to main power becomes high, because of the ease and certainty with which exact measurements can be made:—

The results can be translated into terms of fuel, and show exactly the cost of the various services performed and their individual efficiency, enabling the whole equipment to be maintained with maximum efficiency. The saving effected from being in a position instantly to locate wastage of power and fuel, and to carry out the necessary adjustments, may easily span the margin between profit and loss.

At the present time, the two main systems are the turbo-electric (§ 960) and the Diesel-electric (§ 960) drive, each of which is applicable in a greater or less degree to many types of vessel, in competition with the steam-engine drive, the direct Diesel drive, and the geared

* 'The Electric Propulsion of Ships,' L. F. Ratcliffe. *El. Rev.*, Vol. 107 p. 439.

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turbine or geared Diesel drive. For large vessels, the turbo-electric drive at present has the field to itself, owing to the limitations in the power of even the largest Diesel engines; whereas the latter are especially suitable for all kinds of small craft, where comparatively small steam turbines would be at a disadvantage in point of efficiency (§ 189, Vol. 1). Most types of steam turbine have been used, notably the Parsons, Curtis, Ljungstrom, and Rateau.

Electrical propulsion has proved consistently reliable, and there is every reason to anticipate its general adoption. Naturally each type of vessel must be considered on its merits, because size, design, and service vary widely; but the adaptability of the method to every circumstance is one of its chief claims.

957. Advantages of Electric Propulsion, Turbo, and Diesel.—The relative merits of the various systems, as applied to different types of vessels, are discussed in succeeding paragraphs; but here the inherent advantages of electrical as against mechanical driving may be touched upon.*

For fuel, the choice lies between coal and oil, and the latter seems to be making headway at the expense of the former. With coal, steam engines or steam turbines are the prime movers, the latter geared for direct driving; turbines are invariably used where generators and motors are to take up the running. With oil, either steam may be generated for use in the same manner; or the fuel may be used directly in Diesel engines, with great gain in thermal efficiency (§ 167, Vol. 1), and these may drive the ship either directly, or with gearing, or through generators and motors. One factor of importance in the matter of oil is that of price control by trusts and rings generally, which may affect the future of liquid fuel, especially as the British Empire embraces so little of the world's supply.

The basic advantage of the electric drive is the ease, efficiency, and flexibility of control of the power. The most economical high-speed turbine or Diesel engine can be used in conjunction with the most economical propeller speed, which is far lower; and both the number and speed of the propellers are independent of the number and speed of the prime movers employed, which can be varied as the conditions demand. The reversal of the propellers is a slow

* For a critical study of some of the disadvantages alleged, see a paper on the subject by Mr. W. J. Calderwood, read before the Junior Institution of Engineers—*El. Rev.*, Vol. 91, p. 638.

business with a direct Diesel drive, and requires a separate special steam turbine where that form of direct or geared drive is used. A steam turbine is an irreversible machine, so the special turbine required for this purpose, together with its gears, revolves idly all the time; and it is also necessarily of much less power than the main turbines—generally about one half. Again, the size and weight of the turbines is increased, and the efficiency reduced, because full advantage cannot be taken of high-pressure, superheated steam, which if suddenly applied, as it must be for reversal, would endanger the comparatively cool reversing turbine. With electric propulsion, reversal is simply a matter of changing the electrical connections, and the whole power of the marine central station is still behind the motors, so that a rapidity of reversal hitherto undreamed of becomes possible. In an emergency, such a possibility may save the ship.

Electrical transmission from the prime movers to the propeller shaft is clearly more flexible than gearing, while the customary enormous length of the propeller shaft itself, with its containing tunnel, will certainly be reduced as experience is gained and the engineers become content with a special motor room close to the working point—already this has been done in some cases. The turbo-electric drive also completely eliminates vibration at all speeds.

Exact power measurement is a self-evident advantage of every phase of electric driving, and is also far simpler than with mechanical driving; and measurement is the foundation of economy.

Any one of the prime movers, of whatever type, can drive all the propellers at reduced speed, but with uniform division of the power between them; thus, if two sets are installed, one will drive the ship at about three-quarter speed with practically full efficiency—a matter of great importance for cruising speeds in war vessels. A ship with three generating sets, and a normal full speed of $11\frac{1}{2}$ knots, can be run on two sets at about 10 knots, or say $88\frac{1}{2}\%$ of full speed, and on one set at about 8 knots, or 70% of full speed. A 25 000 H.P. vessel making 22 knots could run at $17\frac{1}{2}$ knots on half full power. The propulsive power varies as the cube of the speed approximately. Furthermore, it is possible to run into port by means of the auxiliary generators, if the main units are out of action for any reason, whereas in the like conditions a mechanically driven ship is helpless. The racing of propellers in a rough sea

can be prevented by the use of an automatic speed governor, to the advantage both of the machinery, the hull and the passengers.

With electric propulsion, the designers are free to place the prime movers in the most convenient position, instead of being compelled to use a location where the propeller shaft can be of reasonable length, though hitherto full advantage has not been taken of this owing to the desire to have the motors in the engine room. The turbo-generators can be placed close up to the boilers, so as to give the minimum length of steam and exhaust (condenser) piping, and maximum vacuum. With the turbo-generators located over the condensers, on a flat above the boiler room, it is possible greatly to reduce the length of the engine room and thus to increase the cargo capacity.

In the matter of weight, for small high-speed vessels such as destroyers, yachts, etc., the geared-turbine drive is lighter than electrical driving; but on large vessels the electrical equipment generally weighs the same as or less than geared-turbine plant, allowing for the greater weight of steam and exhaust pipes, the oiling installation, and the longer shaft.* Ordinary reciprocating engine equipment weighs about double that for a corresponding electric drive.

The ordinary method of conveying instructions to the engine room by ship's telegraph, where they have to be read off and acted upon, takes up time which in an emergency may be of vital importance; with electric propulsion the whole control can be directly exercised from the bridge, just as from the driver's cabin of an electric train, by means of a master controller (§ 741) which has no personal equation and which acts instantaneously. If desirable, additional master controllers can be installed elsewhere, as in multiple unit trains (§ 871), only one being in action at any one time.

With both turbo-electric and Diesel-electric drive there is the important consideration that substantial fuel economy is effected, with a resultant saving both in dead-weight to be carried and in cargo space occupied. Against this, the actual plant may take up more room and displacement than steam plant alone, and will be more expensive in first cost. The extra weight and space are

* The U.S. collier *Jupiter* is electrically driven, having 7 000 H.P. of plant weighing 156 tons; her sister ship *Neptune* has geared turbine equipment weighing 150 tons, and extra piping, etc., increases this difference.

compensated for to some extent, if not entirely, by the smaller and lighter prime mover of higher speed, and by the shorter shaft and shaft tunnel; the extra cost, it is claimed, is justified by the higher overall efficiency, higher schedule speed—especially in bad weather—and extra cargo space in lieu of fuel. There are, again, double-conversion losses, but these are offset by the higher efficiency of the high-speed prime mover and by the use of superheated steam * as well as by better maintenance of the original high efficiency than with a mechanical drive.

Table 206 illustrates the improvement in efficiency which may be obtained by the use of superheated steam:—

TABLE 206.—*Superheat and Fuel Saving.*

Steam.			Approximate % of Total Heat in Steam Available for Work.		Percentage Saving in Fuel.
Pressure, Lb. / sq. in. Abs.	Temperature, Fahr.				
	Of Superheat.	Total.	%.	Increase %.	
200	50	432	30.7	—	—
200	200	588	31.8	0.9	3.0
300	50	467	32.6	1.9	6.2
300	100	517	33.0	2.3	7.5
500	100	567	35.3	4.6	15.0
500	233	700	36.3	5.6	18.2

Temperatures up to 600°-650° F. are used in electric cargo vessels, but the pressure is generally 200-250 lb. per sq. in. If 500 lb. were used, there would be a great saving in fuel.

Objections have been raised, on the score of danger, to the use of pressures up to 1 000 V or more in the main propulsion circuit, where they are necessary for economy in cable connections; but such pressures are common in industrial applications on land and are no more dangerous than live steam. In fact a short-circuit can be met instantaneously by a high-speed circuit-breaker (§ 372 (3), 5th ed.), whereas a broken steam connection generally has more serious results in the confined spaces of a ship than on land.

* A claim to have developed 1 H.P. for 8.5 lb. of steam per hr. has been made. *Shipbuilding and Shipping Record*, Dec. 30, 1920.

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Mention has already been made of the rapidity of reversal possible with an electric drive, and it follows that there is also rapidity of manœuvring. It is on record that the 3 600-ton vessel *Cuba*, using synchronous motors, can stop the propeller from full speed in $2\frac{1}{2}$ secs. and cause it to be running full speed astern in a further $7\frac{1}{2}$ secs.; the vessel itself can be stopped from full speed ahead in 140 secs., as against from 4 to 10 mins. with a reciprocating engine drive.

Mr. W. E. Thau gives the following comparison* (Table 207), based on a 3 000 H.P. ship making 14 single journeys per annum over a 4 000-mile course at 11 knots; all items of machinery, water, fuel, etc., are taken into account, and the same steam conditions are assumed in both cases.

TABLE 207.—*Weight and Fuel Consumption with Various Systems of Ship Propulsion.*

Drive.	Fuel Consumption.	Weight of Machinery.
Geared turbine	1·0	1·0
Turbo-electric	1·06	1·05 to 1·1
Diesel direct	0·49	1·1 to 1·25
Diesel-electric	0·57	0·75

Commander S. M. Robinson, of the U.S. Navy, compares† the *New Mexico* (turbo-electric) with the sister battleship *Idaho* (geared turbine for cruising up to 17 knots and direct turbo drive above that speed), and also with the *Mississippi* (geared turbine up to 15 knots and direct drive above) as follows:—

Extra fuel consumption of *Idaho* and *Mississippi* is about
 20 % at 10 knots; 42·7 % at 13 knots; 47·8 % at 16
 knots; 32 % at full power.

It is generally believed that the U.S. Navy Department finally embarked on its electric battleship programme on the results of a comparison between three colliers: the *Cyclops* with triple-expansion reciprocating engines; the *Neptune* with geared turbines; and the *Jupiter* with electric propulsion, using slip-ring induction motors. Each vessel is of 20 000 tons displacement and 12 000 tons cargo

* *Journal Am. I.E.E.*, Vol. 40, p. 629.

† *Marine Engineering*, May, 1920.

capacity. The comparison is shown in Table 208, but it does not follow that the data necessarily apply to vessels of other types and for other services.

TABLE 208.—*Comparison of Three 20 000-ton Colliers.*

	<i>Cyclops.</i>	<i>Neptune.</i>	<i>Jupiter.</i>
Weight, propelling equipment only, tons	280	150	156*
Steam consumption at maximum speed; lb. per shaft H.P.-hr.	14.0	13.4	11.1
Ditto, per cent. greater than <i>Jupiter</i>	26	20.7	—

At its most economical speed (12 knots) the *Jupiter* uses 49.1 tons of coal in 24 hours, which is 36 % better than any other ship afloat up to that date (1919). In smaller vessels the weight comparison is somewhat less favourable to electric propulsion, but there are many indirect savings.

958. D.C. and A.C. for Ship Propulsion.—Both D.C. and A.C. are used, and are likely to continue in use, for marine propulsion, where questions of standardisation of plant, voltage and frequency are less important than on land. Generally speaking, D.C. is at present used chiefly with Diesel engines and on the smaller classes of vessel, and A.C. exclusively with steam turbines and on large ships. For D.C. the propulsion motors are usually shunt-wound, with constant excitation. Ward-Leonard control is often used where there are two or more shaft motors.

In the case of A.C., American practice favours 2-pole turbo-generators running at 3 000 r.p.m. normal speed, giving 50 cycles, with 60-pole induction or synchronous motors (synchronous speed 100 r.p.m.). Thus the normal speed reduction is 30 to 1, to give a propeller speed of 100 r.p.m., which is about the most efficient for merchant vessels. Provision is made to vary the turbine speed, and therefore the propeller speed, between 20 and 110 % of the normal. For a turbine drive, A.C. generators have a definite advantage (§ 145); while for a Diesel drive, with its considerable cyclic variation in speed, the D.C. dynamo is particularly suitable and an alternator less so.

* Capt. Durnall, in a paper read before the Institution of Marine Engineers in 1911, estimates that by the use of squirrel-cage induction motors, eliminating two water-cooled resistances of $5\frac{1}{2}$ tons each, this figure could be reduced to 145 tons.

Mr. H. M. Hobart, however, has suggested * the use of A.C. at very low frequencies with Diesel-engine drives:—

If the Diesel-engine's speed is 210 r.p.m., a 4-pole generator will have a periodicity of only 7 cycles per sec. Induction motors for this low periodicity and for customary propeller speeds have very attractive characteristics. If the propeller speed is 70 r.p.m., the motor will have 12 poles. For medium powers (say 500 to 1 000 H.P.) such a motor will have convenient dimensions and be of low cost. Its power factor will be of the order of 0.95 at rated load, and about 0.80 at $\frac{1}{2}$ -load. For a 60-cycle, 70-r.p.m. motor the power factor would be about 0.8 at full load and 0.5 at $\frac{1}{2}$ -load. The full-load efficiency of the 7-cycle motor will be 1 or 2 % higher than that of a 60-cycle motor for this speed and output, and will be about 5 % higher at $\frac{1}{4}$ - to $\frac{1}{2}$ -load. The stalling load of the 7-cycle, 70-r.p.m. motor will be very high indeed, and consequently it can be rated up to its heating limit. With the application of modern insulating materials and processes, and modern knowledge of methods of forced cooling, such a motor will be light and compact, and of low cost. These considerations also apply to low-periodicity synchronous motors.

While this low-periodicity proposition is especially applicable to the Diesel-engine drive, it should also receive careful examination for the case of the steam-turbine drive—at any rate for medium powers. In this case mechanical speed reduction gearing would be interposed between the turbine and the generator. The turbine might, for example, run at 4 000 r.p.m. and drive a bipolar generator at 500 r.p.m. The periodicity would then be 8.3 cycles per sec. For a propeller speed of 125 r.p.m., the motor would be built with 8 poles, and would have the attractive features already described. This is a very different proposition from that which has already been employed on several electrically-propelled ships of interposing gearing between the propeller and a high-speed motor. In the latter case the low-speed wheel runs at the speed of the propeller (125 r.p.m.), as against 500 r.p.m. in the method suggested. The cost of a mechanical speed-reducing gearing depends upon the speed of its lowest speed member, and becomes more expensive the lower the speed of this member. Also in the latter case the direction of rotation of the gearing is reversed when reversing

* *El. Rev.*, Vol. 91, p. 746.

the ship, and its speed changes when changing the speed of the ship. In the former case the gearing always runs at constant speed in one direction.

If gearing is required, it will be cheaper and will endure better if it is placed between the turbine and the generator instead of between the motor and the propeller.

A.C. motors for this work may be either squirrel-cage or phase-wound induction motors or synchronous motors. The squirrel-cage type (§ 682) is the simplest, unless a double-wound rotor is used, giving high resistance at starting, but the starting and reversing characteristics are inferior to those of the phase-wound rotor. The power factor of both types is about 70 % on full load, under the conditions of design imposed by marine work; but while phase-advancers could be used, it is doubtful if they are justifiable. A synchronous motor can have an air-gap of about $\frac{1}{4}$ in. without sacrificing other desirable characteristics, and its power factor can be unity or leading, saving both cost and weight in the generators and cables. Mr. H. M. Hobart (*Loc. cit.*) points out that this property is likely to be made more use of when it is realised that with a leading current part of the generator excitation will be obtained from the stator windings, thus decreasing the burden placed on the rotor of the generator.

American practice is to use a pressure of 1150 or 2300 V for 3-phase turbo-alternators, with low-pressure excitation (125 V). Exciters are usually separately driven by engine or turbine for supplying the main generator field, the control circuits, and the fans for ventilating the main motors; they are generally in duplicate, or at least a spare set is provided.* Often other auxiliaries are also driven from them (§ 964).

Wound-rotor induction motors are favoured for battleships, the arrangements being such that travelling is possible at either cruising or full speed on the normal frequency of generation, one alternator being used for cruising and two for full speed, with nearly the same high efficiency in both cases. The turbine speed can, however, be altered to vary the frequency of the motor supply, while the alternator field can be adjusted to give variable voltage to the motors. Alternators for this service are very similar to standard land machines, except for the above difference in working

* *Gen. El. Rev.*, Feb., 1921, p. 139.

with variable frequency and/or voltage. Special importance is naturally attached to perfect reliability. Electric thermometers are used for the continuous indication of stator and rotor temperatures; heating coils in the end-coils prevent condensation when the machine is standing idle; a steam pipe within the end-shield provides steam to extinguish fire, should it occur, the outlet damper in the ventilating duct being then closed.

The cascade arrangement of polyphase motors (§ 727), unless coupled with a pole-changing device (§ 725), gives only full speed and half speed, and also lowers both the power factor and the efficiency; the latter (according to *L'Industrie Electrique*) by 5 %, where the efficiency of each motor is 94 %, and by 2 %, where it is 96 %. Both the wide speed ratio and the need for rigid connection of the motors are disadvantages on board ship. Variations of the system, however, are stated* to have been devised to adapt it to marine propulsion.

Except in very large vessels, a single turbo-alternator is generally sufficient, and it can serve a single shaft motor or two such in parallel as required. If two turbines are required, each generator can serve its one or pair of motors independently when full power is required, while one generator can serve all the motors at reduced speed and power. Thus there is no need to parallel the alternators, which would offer some difficulty under marine conditions, especially where speed control is effected by changing the speed of the turbines. Consequently, each equipment can be designed as a whole, turbo-generator and motor comprising a complete unit.

959. Control Instruments and Cables.—An electrically propelled ship is a combination of a floating power station, a workshop, a store and a multiple-unit controlled train rolled into one, but a short paragraph must suffice for the above heads.

Control.—With D.C. supply, the operations of starting, stopping, reversal and speed control are much the same as in land applications to vehicles or reversible machinery. With 3-phase induction motors, these operations are respectively effected by closing or opening the circuit and by reversing all connections between generator and motor. Speed can be varied from $\frac{1}{3}$ up to full speed by varying the turbine speed. Water-cooled resistances are used in the motor circuit for starting and reversing. In order

* Miles Walker in the *Electrician*, April 18, 1923.

to secure stable and efficient operation and fine speed control at any desired frequency, the voltage of the alternator can also be varied by a field regulator.

Instruments.—Revolution indicators of the magneto type are used on both turbine and propeller; in the main circuit are ammeters, voltmeters and wattmeters, together with an ammeter in the generator field and one also in the motor field, if synchronous motors are used. In addition, as already mentioned, electrical temperature indicators are used for the generators, exciters and motors.

Cables.—In American ships, lead-covered, iron-armoured cables, with varnished cambric insulation, are used for low-tension D.C. circuits; these are not run in conduit, but overhead, well supported and accessible for inspection and painting. A hot, damp, salt-laden atmosphere is a severe test of quality. Rigid clamping is in all cases necessary to prevent abrasion due to vibration. For main cables between generator and driving motor, practice varies according to whether there is any risk of flooding. Where the motors are in the engine room, and therefore safe from water, varnished cambric insulation is used, with an earthed copper tape wound outside as a mechanical protection and a safeguard against shock. Braid and twine are added outside the copper tape as a further protection against corrosion of, or damage to, the sheath, and fire-proof paint is served on this. If flooding is possible, a rubber sheath is added between the cambric and the copper sheath. In all cases single-core cables are preferable to multicore.

960. Turbo-Electric and Diesel-Electric Driving.—The relative spheres of the two chief methods of generating power for electric propulsion may now be briefly considered.

The Turbo-Electric Drive.—The high-speed steam turbine is the most efficient steam-driven prime mover (§ 167), but in marine work it ordinarily suffers from the disadvantage of having to drive a slowly revolving propeller. Attempts to slow down the one component and to accelerate the other, so as to render a direct drive feasible, have not met with success, so that either mechanical gearing or electricity must be used as a go-between. In reasonably large units the superiority of the high-speed steam turbine in point of efficiency, lightness and small space taken up, compared with the low-speed turbine or reciprocating engine, is such that it is worth while to use it in conjunction with one of the above means of reducing the speed before reaching the propeller. It might appear

that gearing would be preferable to the inevitable complication of generators, cables, switchgear and motors; but, in the first place, high-powered gearing is costly and has not proved an unqualified success, while it does nothing to simplify the problem of reversing; and, secondly, electric propulsion is almost if not quite as efficient as new gearing in first-class condition, and is far easier to maintain in its original condition. Furthermore, it provides for easy, efficient and flexible control, including reversal. Taking the efficiency of both generator and motor as 96 %, the overall efficiency including cable losses should be over 92 %, and it has, in fact, reached 94 % in large American vessels; with double-reduction gearing, when new, the efficiency is about 92 or 93 %, which may drop heavily as wear and tear proceed. All mechanical gears are subject to abnormal tooth pressure where the reduction is large; there are mechanical and thermal changes in meshing; and torsional distortion creates unequal stresses. Admittedly the single-gearred turbine, for speed reduction up to 20 to 1, is both reliable and highly efficient, a gear efficiency up to 98 % being claimed for it when new. Double-reduction gearing, for a 50 or 60 to 1 reduction has an efficiency when new up to about 95 %, but has given trouble by vibration, noise and rapid wear. Electrical machinery can be maintained for many years at its original high efficiency, as well on sea as on land.

Mr. W. J. Belsey compares* the guaranteed steam consumption per S.H.P. of a geared turbine and a turbo-electric drive of the same power. With the latter, and with one turbine driving two motors (10 200 H.P.) the consumption given is 10·9 lb. as against 12·25 lb. for the geared turbine, or a difference of 11 % in favour of electricity. At full power the consumption was 10·5 lb. for electricity against 11·2 lb. for the geared drive, or a difference of 6½ %. In summing up, he points out that a more efficient turbine can be designed for electric driving than for geared driving because of increased efficiency due to—

- (1) The use of the higher speed turbine;
- (2) The elimination of the reverse turbine losses, which are absent with an electric drive;
- (3) The elimination of all cross-over connections between the turbines, as the electric turbine is built with one casing;
- (4) The lesser number of packing glands and sealed cells.

* 'Electric Transmission of Power for Propelling Ships.' *Proc. Rugby Engin. Soc.*, April, 1928.

Mr. Belsey also states (*loc. cit.*) that the overall efficiency from the Diesel engine coupling to the propeller shaft coupling, including excitation losses, varies from 88 % with 2 500 S.H.P. to 82½ % with 375 S.H.P.

Diesel-Electric Drive.—As already stated, D.C. is preferable to A.C. where Diesel engines are used, and the generators may conveniently be coupled in series—for it is usual to have at least two sets, and often four or six. At present these sets are only suitable for comparatively small powers, and therefore for the lighter types of vessel; but in course of time larger units will no doubt be evolved.

The Diesel engine (§§ 179, 180) is easily the most efficient prime mover available for ship propulsion; and it remains so when electricity is employed as a medium, as the double transformation is equally necessary with turbines. And whereas the reversing of the ship, with a direct Diesel drive, involves the use of compressed air for reversing the engine itself, the controller alone effects this far more rapidly with Diesel-electric propulsion. The inherent slow speed of the Diesel engine is a disadvantage for driving generators, making very heavy dynamos necessary, but this can be met by the use of gearing, with a net gain. Any required number of sets can be installed; thus four 220-V D.C. Diesel generators in series can be used to supply two 440-V motors, likewise in series on the shaft. Four or six comparatively small sets have the advantage over one or two large ones in the matter of cooling; for while the available cooling surface varies as the diam.² of the cylinder, the amount of heat developed varies with the volume, or the diam.³.

In small and medium-sized vessels the total cost of high-speed (300-350 r.p.m.) Diesel engines and electric propulsion equipment is as low as that of low-speed (100-120 r.p.m.) direct-coupled engines, so that all the advantages of electric propulsion are clear gain. In larger vessels, the use of electricity makes it possible to use more oil engines than would be practicable with direct coupling, thus getting full advantage of internal combustion engines in the higher powers, the output of individual engines at their most efficient loading being added in the electrical driving circuits. Frequently twin screws are used in plain Diesel ships of a size that does not really require them, because the economic speed of a single propeller is lower than that of the engine, a difficulty entirely overcome by electric propulsion. Again, the engine and generator

sets can be placed wherever the designer chooses to put them—even on different decks if it were for any peculiar reason desirable. There is complete freedom of choice as regards the size and speed of the sets, and each engine runs at constant—and the most economical—speed and in one direction only. It is true that on small vessels (up to 3 000 H.P.) the conversion losses amount to 10 or 12 % between the engine and propeller shafts, but on the other hand, all the advantages enumerated in paragraph 957 are obtained.

E. D. Dickinson gives the following comparison * (Table 209) between the average for six Diesel engines (of four different makes) for electric driving and five other engines (also of four makes) for direct propulsion:—

TABLE 209.—*Relative Diesel Weights for Direct and Electric Drive.*

Drive.	Diesel Engines.			Weights, Lb.	
	Number and H.P. each.	r.p.m.	Weight per S.H.P., Lb.	Engine only.	Engine and Electrical Gear.
Electric	3 × 1 090	238	152	496 000	821 000
Direct	2 × 1 555	105½	380	1 180 000	1 180 000

This table shows a saving of 30 % in weight in favour of electricity; and there would be a further saving due to the use of only one shaft and propeller.

Separate generator excitation, either from auxiliary sets or from direct-coupled exciters on the main sets, is usually adopted, in order to give the largest possible range of speed control, the motor shunt excitation being constant and often obtained from the separate exciters also. With series coupling of the main armatures it is not necessary that their speeds shall be identical, as it would be in parallel running. The main sets are available in port for any other work requiring power (§ 964) thus saving the cost of the usual auxiliary sets.

In a paper read before the American Society of Naval Architects in 1926,† Mr. W. E. Thau deals exhaustively with the advantages

* *Gen. El. Rev.*, Dec., 1921, p. 995.

† *Shipbuilding and Shipping Record*, February 3, 1927.

of Diesel-electric propulsion on tug boats, lake cargo vessels, tankers, yachts, fireboats, ferry boats and passenger ships, for all of which the requirements vary greatly (*see* § 964). He adds a table of 59 vessels of from 60 up to 2 600 H.P. equipped with this drive up to 1927.*

Warships generally (§ 961) require more power than can at present be arranged for with Diesel engines; but the submarine is an exception. The present high development of the Diesel engine is largely due to the activities of German submarines during the war; and D.C. is invariably used in these vessels because secondary batteries are used for driving the motors during submergence.

961. Examples of Turbo-Electric Warships.—The Diesel engine is unsuitable for all but the smallest auxiliary types of war vessel;† but there is no such limitation in the case of turbo-electric driving, which is fast coming into use in the United States Navy. Of the advantages already enumerated and discussed in paragraph 957, that which especially applies to ships of war is the capacity for maintaining either full speed or cruising speed with equal economy in fuel consumption. A merchant vessel is usually only required to travel dead-slow in and around a port, and very seldom at half or three-quarter speed (though she may require forcing to make up lost time), whereas the normal cruising speed and horse-power required by a battleship or cruiser are far below what must be possible at short notice on active service.

Mr. W. L. R. Emmet has pointed out‡ that on fair assumptions an electrically propelled cruiser, running at a cruising speed of 19 knots, will use 0·85 lb. of oil fuel per S.H.P.-hr., whereas a geared ship in other respects similar would require 1·27 lb.

Such an electric ship could run at 19 knots from England to the Falkland Islands, and, starting with 2 300 tons of oil fuel, would have 200 tons left on arrival. A similar geared ship, filled to equal displacement by carrying 2 835 tons of oil (*i.e.* adding the difference in the weight of the two equipments) could not reach at this speed within 700 miles of the distance.

Progress in this new development has been phenomenally rapid, and coincident with the immense increase of the American Navy.

*The list of course includes many boats which would not appear in Lloyd's Register, as quoted early in this chapter (§ 956).

†An exception is found in the huge floating dock for Singapore—*see El. Rev.*, Vol. 102 (1928), p. 765.

‡Paper read during the 64th session of the Institution of Naval Architects, March, 1923, entitled 'Electric Ship Propulsion.'

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It is only possible here to give bare details of a few characteristic vessels to illustrate the evolution of the new departure.

The U.S. battleship *New Mexico* (32 000 tons) uses oil fuel for the boilers. She generates 37 000 H.P. and is propelled by four 24 or 36-pole induction motors of 7 000 H.P. each,* giving a cruising speed of 19 knots and full speed of 22 knots. The following comparison (Table 210) between this ship and others of the same class is instructive:—

TABLE 210.—*Steam Consumption in Battleships.*

Vessel.	Propulsion.	Propeller Speed, r.p.m.	Steam per Effective H.P.-hr. (allowing for Difference in Propeller Efficiency).		
			12 kn.	19 kn.	21 kn.
<i>Florida</i>	Turbine	328	31·8	24·0	23·0
<i>Utah</i>	"	323	28·7	20·3	21·0
<i>Delaware</i>	Reciprocating	122	22·0	18·7	21·0
<i>New Mexico</i>	Turbo-electric	175	17·3	15·0	16·4

So long ago as 1920 the following comparison (Table 211) was made† between the ships of the *Tennessee-New Mexico* type and projected new vessels:—

TABLE 211.—*Comparison of American Warships.*

	<i>Tennessee.</i>	New Battleships.	New Battle-Cruisers (<i>Lexington</i> and
Length overall, feet	624	684	874
Beam, feet	97	105	90
Draught, feet	31	33	31
Displacement, tons	33 000	33 200	43 500
Speed, knots	21	23	35
Guns in main battery	12	12	8
Size of guns, inches	14	16	16
Shaft horse-power	30 000	60 000	180 000

The U.S. battleship *Maryland* (33 000 tons)‡ has two Curtis turbo-generators each developing 28 000 H.P. at 2 030 r.p.m.,

* Full description in *Shipbuilding and Shipping Record*, April 10, 1919, p. 434.

† 'Electric Propelling Machinery of the Future Navy.' *El. Rev.*, Vol. 87, p. 486.

‡ *Shipbuilding and Shipping Record*, April 11, 1921, p. 171.

which drive four induction motors each of 7 000 H.P. at 170 r.p.m. for a speed of 21 knots. With one generator, a speed of 17 knots is attained.

The U.S. battleship *Washington*, a sister ship of the *Tennessee* (see Table 211), developed 30 900 H.P. on trial, four 8 300 H.P. motors being used for propulsion. She was brought to rest from full speed (21 knots) in 3 mins. and then driven astern at 15 knots.

The U.S. battleship *Colorado* has two 15 000 kVA turbo-generators driving four 8 375 H.P., 185 r.p.m., two-speed induction motors with separate 24 and 36-pole stator windings,* each rotor having a 3-phase, 2-parallel, star winding with balancer connections operating on the 24-pole winding, but short-circuited on 36 poles; thus making the rotor squirrel-cage. Excitation and auxiliaries are provided for by three 300 kW geared turbo-dynamos, 240 / 120 V, D.C. Control of both generators and motors is effected from a central control room. The main current is handled by manually-operated circuit-breakers, interlocked in such a manner that the field circuit must be broken, and the steam control reduced, before a circuit is opened. Forced ventilation is used for both generators and motors, and recording thermo-couples show the temperature of the windings. Reversing and manœuvring are done with the 24-pole connections, the motor being regulated by liquid rheostats.

Four of the early U.S. vessels—*Indiana*, *Montana*, *South Dakota* and *North Carolina*—were equipped with two Westinghouse 28 000 kVA impulse-reaction type turbines, using steam at 265 lb. and 50° F. superheat, coupled to 3-phase, 60-cycle, 5 000 V alternators; the four propelling motors being of 15 000 H.P. each.

Before the Washington Conference on naval disarmament, the U.S.A. had begun work on six electrically driven battle-cruisers (*Lexington* and *Saratoga* class) of no less than 180 000 H.P. each (see Table 211), a power exceeded by but few central stations in the world.† The design includes four Westinghouse turbines of 49 750 H.P. each, coupled to 40 000 kVA, 3-phase, 51·3 cycle, 5 400 V generators, driving eight wound-rotor motors—two per propeller—of 22 500 H.P. each. By way of comparison, the British battle-cruiser *Hood*, which is driven by geared turbines, has a total of 140 000 H.P.

* *World Power*, April, 1924, p. 199.

† *EL. Rev.*, Vol. 87, p. 486.

Other Navies than the American have not at present gone far in electric propulsion, preferring to 'wait and see' how these latest Brobdingnags of the sea work out in practice. The British Navy, however, has fitted the minelayer *Adventure* with an installation of two 2 100 H.P. Diesel-electric A.C. sets, with a motor for each of the twin screws; a small beginning, truly.

962. Electric Propulsion of Cargo Vessels.—So far as this country is concerned, the cargo vessel is pre-eminent, the whole naval position of Great Britain having arisen out of the carrying trade, to protect which our once unchallenged Navy grew up. With large displacement, and low speed and horse-power, the experimental work on electric propulsion would naturally fall to this class of vessel, though the United States, being in a hurry to put us in the second place while we are still hard up, has gone straight to ships of war.

At a joint meeting of the American Institutes of Electrical and Mechanical Engineers, in 1921, Mr. Eskil Berg, comparing various drives, concludes that:—

In cargo vessels up to about 1 500 H.P., geared turbines are both lighter and cheaper than electrical methods of propulsion, and the problem of making and maintaining the gears is relatively simple. For low speed, single-screw cargo vessels of about 2 500 to 3 000 H.P. the geared drive is rather lighter and the transmission efficiency of gears higher than that of electric propulsion. Allowing for losses in reversing turbines, power for oil circulation, packing losses, etc., the overall efficiency of the electrical drive is equal to or better than that of gearing. If the motors are placed aft, saving largely on the propeller shaft, the electrical equipment is lighter and cheaper than the geared drive. With twin-screw ships of about 6 000 H.P., the electrical drive is distinctly cheaper, lighter and more efficient if one turbo-generator is used to drive the two propellers; if two are used, the comparison becomes as in the case of 3 000 H.P. single-screw vessels.

The fruit trade is one of the most important lines of cargo work from our standpoint, as the auxiliary power required is very large; so a vessel of this type will be described as typical.

The first Diesel-electric ship built in Great Britain was the 3 300 H.P. 14-knot cargo ship *La Playa*,* one of four similar vessels constructed by Messrs. Cammell, Laird & Co., in conjunction with the British Thomson-Houston Co. for the fruit trade. She is essentially a refrigerating vessel for the transport of bananas, so that the plant as usual fulfils the double function of propulsion and auxiliaries; but in this case the refrigerating plant is the key

* *El. Rev.*, Vol. 93, p. 621.

to the situation. Four 825 H.P. Cammell, Laird-Fullagar (Diesel) engines, running at 250 r.p.m., are directly coupled to two generators each, *viz.* a 500 kW, 10-pole, differential compound, commutating-pole main generator, supplying at 220 V for propulsion, and an auxiliary 220 kW shunt generator in tandem with the other, for working the refrigerators and the auxiliaries, and for exciting the propelling generators and motors. The main generators are in series, so that 220, 440, 660, or 880 V can be obtained at will; consequently the fuel consumption per S.H.P. varies but little. The main twin propelling motor is rated at 2 500 H.P. total at 95 r.p.m. and 880 V, and is placed aft, not in the engine room. Control is effected entirely by means of the field circuit.

The fields of both generators and motors are excited from the auxiliary generator, the former by potentiometer system for starting, stopping, and reversing. Full power reversal takes only 8 secs. with the motor-operated field regulator, and 30 secs. using the stand-by manual gear. Acceleration and deceleration are controlled by an overload current relay; the control lever switches in and out a servo-motor, which sets the potentiometer field regulator to the corresponding position; and this motor stops temporarily if overloaded beyond the setting current of the relay. With one engine working, the propeller speed is 63 r.p.m.; with two, 76 r.p.m.; with three, 88 r.p.m.; and with all four, 95 r.p.m. With only one motor in use, three-quarter speed is obtained. The propulsion generators can, if necessary, be changed over to auxiliary work when not otherwise required. The fuel consumption per S.H.P. is the same at quarter, half, three-quarter or full load, so long as each engine in use is fully loaded. In case of a rapid reversal, the propeller drives its motors as generators, and regenerative braking (§ 900) is obtained by driving the engines through the generator, as in the case of railways. If the engine speed rises so far that the fuel supply is completely cut off, then the motor which sets the reversing rheostat is temporarily stopped. The centre point of the propeller motors, where the two armatures connect up in series, is earthed through a current-limiting resistance and a circuit-breaker, which latter is shunted through an alarm bell. The earth connection is opened once on each watch, to test the bell and to measure the leakage current, during which interval it would be possible to receive a shock at 880 V by touching live metal in the circuit.

The increased bin capacity of this boat, as compared with a similar one with reciprocating engines, is 26·3 %, and as compared with one having a turbo-electric drive, 29 %.

Among the earlier British cargo vessels with electric propulsion, the *Wulsty Castle* (6 000 tons) has two Ljungstrom turbo-alternators of 625 kW each—two alternators being used on each shaft—working at 60 cycles, 650 V and 3 600 r.p.m. The two enclosed slip-ring motors of 750 H.P. each, at 714 r.p.m., are geared to the propellers, which run at 76 r.p.m. Synchronising gear is provided, and each motor can be run from either generator, singly or in parallel. Reversal is carried out by reversing two phases when the rotor circuit is broken.

The Atlantic oil-tanker *Brunswick* of 17 680 tons, is a Diesel-electric vessel with four 600 kW D.C. sets, which are worked in series, giving 1 000, 750, 500 or 250 V as required for the speed. The propelling motor is of 2 800 B.H.P., with two armatures in series on one shaft, control being effected by variation of the main voltage and excitation. When stopping in order to reverse, the rotation of the propeller by the water is used regeneratively to drive the engines, thus enabling quick reversal to be carried out; the friction load of a Diesel set being some 33 % of its normal output implies considerable economy. All the auxiliaries are electrically operated, to the extent of 550 B.H.P.

963. Examples of Electrically-Propelled Passenger Ships.
—While the advantages of electric propulsion are more pronounced in ships of war and cargo vessels than in liners, they are nevertheless considerable in the latter class. Without recapitulating what appears in paragraph 957 of this chapter, it may be said that the adaptability of the plant location to suit the passenger and cargo accommodation is among the more important benefits obtained; and this accommodation is very sensibly increased at the same time. As regards reliability, which is of prime importance, the majority of breakdowns which can occur to electrical machinery are easily repaired, while, in the event of a major breakdown, such changes can be made in the connections as to enable a large fraction of the total power to be used. While regular travel at comparatively low 'cruising speed' is mainly confined to warships, many passenger boats are operated on different schedules in different months, and all require great flexibility in speed when arriving at or leaving port, together with the capacity to make up

time lost owing to head winds or stress of weather. Electrical driving has an undoubted advantage over direct driving for such manœuvring and reduced-speed work.

The earliest electric passenger vessel was a salvaged American wreck, the *Cuba*, of about 3 600 tons and carrying 260 first-class passengers.* The prime motive power is a single 8-stage impulse turbine of 3 350 H.P. at 3 000 r.p.m., driving a 3-phase, 50 cycle, 1 100 V, 2 350 kW alternator. A synchronous motor (starting as an induction motor, without the D.C. field) drives the propeller at 100 r.p.m., and D.C. generating sets are installed for excitation and auxiliaries.

In reversing, the motor is automatically connected to function as a generator, returning power to the turbo-generator, thus acting as an electric brake and bringing the propeller to rest. It then operates as an induction motor to start the propeller in the reverse direction and, finally, as a synchronous motor driving the ship full speed astern. It is a noteworthy fact that on the official trials the main motor was brought from full speed ahead to a dead stop in $2\frac{1}{2}$ secs., and to full speed astern in $7\frac{1}{2}$ secs., while the vessel itself was brought from full speed ahead to a dead stop in 140 secs.

On the French merchant ships employing electric propulsion, the *Guaruja* and *Ipanema* (7 880 tons), two Ljungstrom turbines are installed, driving 3-phase, 1 200 V, 50-cycle, 1 000 kW alternators. As these boats are used partly as passenger and partly as cargo vessels, two different motors are installed; one of 1 200 H.P. with 48 poles for a cargo speed of 10 knots at 123 r.p.m. and one of 2 800 H.P. with 36 poles for passenger service, at 13 knots and 163 r.p.m.—one or both turbines being used with the smaller or larger motor respectively. The entire control is carried out in the engine room, though the motors are not in it, but right aft.† The oil-fuel consumption on trial, at cargo speed, was 1.05 lb. per S.H.P.

The 19-knot turbo-electric liner *California*, of the International Mercantile Marine, is a more recent example of this form of drive, and is one of several vessels of the same build. She is 601 ft. long, with a draught of 32 ft. and a gross tonnage of 21 000. The twin screws are driven by 5 253 kW, 3-phase, synchronous induction type motors, at 110 r.p.m., 3 700 V.‡ There are two Curtis (impulse) steam turbines, each having 16 stages and

* *Shipbuilding and Shipping Record*, Feb. 3, 1921.

† *Ibid.*, Aug. 10, 1922, p. 176, and *Elec. Industries*, Aug. 2, 1922, p. 935.

‡ *El. Rev.*, Vol. 102, p. 163.

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developing 6 750 S.H.P. at 2 640 r.p.m., direct-coupled to a 5 250 kW 3-phase alternator. Steam is generated at 275 lb. per sq. in. with 120° F. superheat. Four auxiliary D.C. 240 V, 500 kW geared turbo-generators are also installed.

The S.S. *Virginia*, a twin-screw, 18-knot vessel of 32 800 tons displacement, having machinery of 17 000 S.H.P., is driven by two synchronous induction-type motors each of 8 500 B.H.P. at 120 r.p.m. With steam at 275 lb. /sq. in. and 200° F. of superheat, and a vacuum of 28½ in., the steam consumption on a 10 000-mile run worked out at 8·1 lb. /S.H.P.-hr., equivalent to 10·85 lb. /kWh, this being inclusive of all auxiliary power of which refrigeration alone accounted for some 800 H.P.*

In addition to the *Viceroy of India*, put into service in 1932, the P. & O. Co. have two more turbo-electric liners under construction; the electric equipment being part of the 117 000 S.H.P. recently installed by the B.T.H. Co. of Rugby. The S.S. *Mooltan* has been fitted with exhaust turbo-electric drive through a motor on the main propeller shaft, as an auxiliary, with excellent results. This comparatively new development is making great headway. The success of the Bauer-Wach system of combining a low-pressure exhaust-geared turbine with a reciprocating steam engine has opened up many possibilities. In this system, the principal feature is the interposition of a hydraulic coupling of the Föttinger type, which makes it possible to cut out the exhaust turbine and part of its reduction gear almost instantaneously, preparatory to manœuvring with engine alone.† The use of an extra motor floating on the driving shaft, as mentioned above, obviates the use of mechanical reduction-gear, flexible couplings and hollow shafts. The losses are consequently more than balanced by the gains.

The turbo-electric luxury liner *Queen of Bermuda*, built by Vickers-Armstrong and electrically equipped by the G.E.C. (Witton),‡ has an overall length of 579½ ft.; breadth 83½ ft.; gross tonnage 22 500; speed 19¼ knots; shaft H.P. 19 300. She is equipped with eight Babcock & Wilcox boilers of standard marine design, having a pressure of 400 lb./sq. in. with steam temperature of 650° F., burning oil under forced draught. The

* *Elec. Rev.*, Vol. 105, p. 697.

† *Shipbuilding and Shipping Record*, Sept. 26, 1929, p. 357.

‡ *Ibid.*, Feb. 23 and March 2, 1933.

engine room contains two 7 500 kW, 3-phase, 3 000 V, 50 cycle G.E.C.-Fraser and Chalmers turbo-alternators running at 3 000 r.p.m.; the alternators having 1 kW heaters embedded in their frames to keep them free from condensation when not in use. The turbine blades are machined from solid bars of stainless steel and individually riveted to the rims. There are overspeed governors and a gear to trip the turbine if the vacuum fails. Flexible couplings connect turbine and alternator. The propellers are each driven by a 3 000 V synchronous motor of 4 750 B.H.P. normal rating at 150 r.p.m., and any motor can be supplied from either alternator. The motors are of the totally-enclosed, salient-pole type, provided with heavy damping windings in the pole faces to develop the extra torque required when reversing, and with both forced ventilation and embedded heaters. Starting and stopping are effected by alteration of the turbine speed and regulation of both alternator and motor fields. Low-voltage switching is used throughout, the reversing switches only operating when all excitation is cut off. For auxiliary purposes, there are four 750 kW geared turbo-generators, while as an emergency standby there is an oil engine-driven 50 kW D.C. generator (on an upper deck) with an Exide 'panic' battery and the 'keepalite' system (§ 430). Electrical pyrometers, indicating at a central spot, record the temperature of the various uptakes, superheater, refrigerating chambers, etc. There are four electric cargo winches and four warping capstans (§ 791). The anchors are handled by electrically-driven capstan heads, exerting a pull of $28\frac{1}{2}$ tons at 38 ft. / min., the motors being of 150 B.H.P. at 400 to 900 r.p.m. Batteries give an emergency supply to the Sperry auto-gyro compass, wireless, telephones, electric clocks, etc. Apart from the ordinary cowl ventilation, the whole of the accommodation is ventilated by the Thermo-tank punkah-louvre system, employing over 100 motor-fan units; in addition, there are some 600 G.E.C. 'Magnet' fans or Gyro two-speed fans. Exhaust ventilation extends to the lower decks, kitchens and baggage room—a matter that will appeal to every traveller by sea, especially in hot climates such as Bermuda. Complete electrically-operated refrigerating plants are provided; two of 39 B.H.P. and two of 70 B.H.P., operating some 44 000 cu. ft. of space. Automatic electric thermostatic fire-alarms are fitted in the cabins, etc., and there are fire detection arrangements throughout. The G.E.C. cooking and heating equipment is a

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special feature, requiring some 600 kW. All pumps are also motor driven. The electro-hydraulic steering gear is of the four-cylinder type, with two 42 B.H.P. constant-speed non-reversing motors each driving a Williams-Janney variable-delivery pump, operated from the bridge by a Brown telemotor; emergency connection can be made to the 'panic' battery in 14 seconds.

964. Accessories and Auxiliaries.—For practically every purpose on board ship, except where A.C. propulsion is used, the employment of D.C. is general; the auxiliary dynamos—whether turbo or Diesel driven—being made large enough for all auxiliary purposes in addition to supplying, in most cases, exciting current for the main generators and motors. It should be possible to operate all auxiliaries when the main generating sets are out of commission, so that auxiliary generators are in any case advisable. Furthermore, the turbo-alternators used for propulsion are essentially intended to be operated on both variable frequency and variable voltage, and are therefore only suitable for their own motors.

The first consideration in a warship must always be reliability, economy being a very secondary consideration, at least on active service; on the other hand, economy and reliability must run in double harness on a merchant vessel.

Many auxiliaries are common to all types of ship; others are special to particular classes, especially to war vessels. Auxiliaries requiring power are scattered all over the ship, and can be easily reached by cables, whereas the losses in long steam pipes and individual steam engines are serious. The obstruction offered by cables is far less than that of pipes, and the liability of the latter to freeze is eliminated. The efficiency of a motor with its cables, especially at reduced load, is far higher than that of a steam engine with its pipe-line, and the motor is safer and more compact. By using meters, the exact consumption can be checked, and it is possible to detect both waste and mechanical or other irregularities. Control of the motors is possible from the bridge or any other convenient point, a single lever sufficing for speed control, forward or reverse, over the whole range of any particular apparatus.

The maintenance required by a motor is much less than that required by an engine; given good design and installation, nothing more is needed than lubrication and cleaning down. The overall cost of electrical equipment is little higher than that of steam

auxiliaries, including their pipe-lines, and the extra cost is more than compensated for by economies in service.

The reliability of electricity is demonstrated by the fact of its use for electric or electro-hydraulic steering gear on practically all Diesel-driven ships; which incidentally effects economy by cutting out a very inefficient donkey-engine which otherwise would be in use throughout every voyage. The steering can be directly controlled from the bridge by a master controller; the motor may operate the rudder directly, or may work the valves of a steam steering engine or of hydraulic gear if preferred. In the latter case, it is essential that the motor shall restart directly and automatically as soon as the supply is restored after a breakdown or stoppage of the plant.

The navigation lights can be coupled in series with an electro-magnet which operates an 'on-and-of' indicator, and, if this shows 'off' when the switch is on, an alarm bell is rung.

The electro-hydraulic system, using a pump driven by a constant speed motor, has advantages for boat hoists, cranes, winches and the like; full power can then be utilised on the motor whatever the speed of the driven machine.

All electrical apparatus on board ship, together with its control gear, must be completely sea-proof and unaffected by saline moisture, as well as able to stand up to rough usage, strain and vibration. It must be capable of operation when at least 30° from the perpendicular. Corrodible metal parts must be avoided, and resistances should be of monel metal (§ 66, Table 6) or similar alloy. Facilities for easy access and simple repair are essential. Standardisation and interchangeability are, here as elsewhere, of use in reducing the number of spare components to be carried and in facilitating repairs or replacements at sea. Lever face-plate or drum-type controllers are generally preferred to contactor gear, but the latter has been successfully used in conjunction with master controllers for high powers, or where the controller is necessarily distant from the motor, as in steering gear.

As regards location, cables are generally placed below the decks, and rheostats also when possible; otherwise the latter may be put in suitable enclosures on deck. Good ventilation is desirable—and difficult to ensure; apart from the direct access of water, there is always condensation due to 'breathing' to be contended with (§ 538), so that drainage as well as ventilation is necessary.

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Casings of all sorts must be vermin proof. Some of the motors, such as those for cargo winches, are only used in port, and others, *e.g.* for anchor windlasses, even more intermittently; these must be unaffected by weeks of idleness, and capable of service at any time.

Warships.—In the British Navy the standard for auxiliaries is 220 V, 2-wire, with a ring main, whereas American practice favours 3-wire, 120 / 240 V. There may be as many as 400 motors on a battleship, aggregating some 2 300 B.H.P.* and varying from fractional horse-power up to 200 H.P. for boat hoists. For the working of heavy turrets, the electro-hydraulic system is used, plain electrical driving sufficing for lighter turrets. For low and high-current density searchlights a motor-generator is generally used, reducing the pressure to 58-62 V with a constant current of 110 A.

So multitudinous are the applications that a mere alphabetical catalogue (Table 212) of the electrically-operated gear on one battleship (*U.S.N., Maryland*) must suffice:—

TABLE 212.—*Electrically-Driven Battleship Auxiliaries.*

Air compressors.	Laundry and tailoring irons.
Air heaters.	Lighting.
Ammunition hoists.	Motor boat ignition.
Anchor windlass.	Potato peelers.
Bake ovens.	Powder-testing oven.
Boat cranes.	Pumps.
Capstan warping.	Range signalling.
Carpenters' shop.	Searchlights.
Cinema.	Steering gear.
Deck fans.	Sterilisers.
Gun elevating.	Storage batteries.
Gun firing.	Telephones, ordinary and loud speakers.
Gyro-compass.	Turret training.
Ice-cream machine.	Ventilating blowers.
Ice machines.	Visual signals.
Kitchen utensils.	Winches, deck.
Laundry.	Wireless telephony and telegraphy.

There are no doubt other uses which do not happen to exist on this particular ship, for instance, submarine signalling and navigation by 'leader' cable.

Merchant Vessels.—Many of the auxiliaries in the above list are also found on passenger and/or cargo vessels—to which one would think the cinema and the ice-cream machine would more

* *El. Rev.*, Vol. 100, p. 575.

particularly apply. Cooking and many of the ordinary domestic appliances are used; electric heating and refrigerating are invaluable; and big liners have electric lifts.

See also data in Table 165, § 780, regarding power in dock-yards and ships; also, § 791 for winches and capstans, and Chapter 31 generally for hoisting and allied services.

965. Electric Propulsion of Special Craft.—Apart from ships of war and merchant vessels, there are other classes of vessel to which electric propulsion is applicable, and for which it is already used, to which brief reference must be made.

Paddle-Wheel Ships.—The paddle-wheel steamer still finds a considerable field in lake, coastal and river service, especially where very light draught is necessary and 'stern-wheelers' are employed. The stern-wheeler, with a single paddle, is inherently lacking in power of manœuvre; the speed of revolution (30 to 40 r.p.m.) is far lower than with screw propellers, and as such vessels spend much time both in avoiding sandbanks and in getting off those not avoided, the normal variation in running speed is large. Independent and instantaneous control renders the Diesel-electric drive very suitable for this class of work, in which the power involved is small. To attain lightness and minimum draught, single-gear driving motors are indicated.

The ordinary pleasure steamer with twin paddles seldom requires more than 2 000 H.P., so here also the Diesel-electric drive is suitable. In many vessels of this kind, there is now a single engine driving two paddles rigidly connected; but with an electric drive there would invariably be a motor to each independent paddle, enabling the boat to turn round practically on its own ground, just as with twin engines. Both in this respect, and in facility for running astern, electric propulsion has an advantage that cannot be gainsaid. Turbo-electric propulsion has also been used* for paddle-steamers for a good many years, both with Ljungstrom and other types of steam turbine of the order of 2 000 H.P.

Ferries.—Apart from freely-running boats, there is scope for electric propulsion on ferry boats with a fixed route, where power can be collected from a strung trolley line, if the span is reasonable, or from a similar line supported on floating or fixed towers where

* *Shipbuilding and Shipping Record*, March 20, 1919, p. 843.

a single span is impracticable. In recent years the double-ended train-ferry, as an alternative to a bridge, has often been used in river and estuary, and for these large units either the self-contained (Diesel or turbo) drive or the overhead trolley line is suitable. As an example, the ferry at the Golden Horn, between Oakland and San Francisco, may be cited; since the present writer last crossed this ferry it has been converted to turbo-electric working. Propellers are installed at both ends of the double-ended boat, each having a 1 200 H.P., 500 V, 125 r.p.m. motor for a speed of 13 knots. Bow and stern are alike, and whichever propeller is for the time being at the bow runs at lower speed—100 r.p.m.—so as to secure zero slip on that propeller. The similar ferry service between San Francisco and Berkely uses a 400 H.P. Diesel-electric drive.*

Barges.—Electrically-operated barges, running from trolley lines along the tow-path, have had considerable success where water transport is freely used. The extravagant proportion of the total cost of coal, coke, iron, and steel, for which railway transport is responsible in this country, is notorious; unfortunately, most of our canals were frozen out long ago by railway competition—ending in purchase and disuse—so that the volume of heavy traffic carried by them is small. A revival of canal transport by electricity, divorced from railway control, is one of those obvious remedies which do not interest hard-hit industrialists; but with the advent of the 'grid' and rural lines it becomes eminently practicable.

An alternative method is to tow barges by an electric locomotive running along the bank; but the cost of the permanent way, and the possibility of having to strengthen the banks to withstand the weight, go far to counterbalance the cost of the first-mentioned system.

It has also been proposed to equip barges for the required low-speed propulsion by motor-driven propellers, and to supply power to a chain of such through a flexible cable from a self-propelled motor boat carrying generating plant. This is practically equivalent to a multiple-unit train on land, and would appear to be the most economical plan in first cost for inland waterways.

* *Compressed Air Magazine*, Nov., 1927, p. 2211. See also 'Application of Electric Propulsion to Double-Ended Boats,' by A. Kennedy and F. V. Smith. *Jour. Am. I.E.E.*, Oct., 1925, p. 1079.

As an alternative to generating plant, accumulators could be used, provided charging and changing stations were built. The energy required, however, is said to be three times that needed with locomotives.*

Tugs.—The Diesel-electric drive is particularly suitable for harbour tow-boats and tugs, on account of the manœuvring power given and the facility with which it is possible to operate the propeller at low speed with a large thrust or at high speed with a proportionately reduced thrust.†

Dredges.—Mention is made elsewhere (§ 842) of electrically-driven dredges for hydraulic mining, and this type of vessel has also been used for ordinary suction and bucket dredging, with power from 500 to 1 600 H.P.

Miscellaneous.—Electrically-propelled coastguard cutters, fire-boats, oil tankers, trawlers, and yachts have also been built to the number of some dozens in the U.S.A.

966. Rules and Regulations Concerning Electricity on Shipboard.—Under the Home Office Regulations relating to the construction and repair of ships, it is specified that direct current only shall be used and the pressure shall not exceed 120 V: (a) for all temporary installations for lighting, power, or heating on a ship under construction or repair; (b) for welding by means of an electric arc, except where it can be shown that the use of A.C. is as safe as that of D.C. at 120 V. All approaches and all parts where work is being carried on must be efficiently lighted, and lights must be provided at deck and other dangerous openings and at all ladders and gangways.

The I.E.E. in 1926 issued the second edition of its 'Regulations for the Electrical Equipment of Ships,' a permanent Committee having been appointed to deal with this matter. These Regulations are on the lines of the 'Wiring Rules' (*q.v.* in Vols. 1 and 2) for land use, being concerned mainly with internal equipment for auxiliaries rather than with propulsion. Important alterations and additions are contained in a supplement issued in 1929.

The American I.E.E. has also published a code of rules—*see* Bibliography below.

* *Elekt. Zeits.*, Oct. 20, 1921, p. 1190.

† 'Electric Transmission of Power for Propelling Ships,' W. J. Belsey. *Proc. Rugby Engineering Society*, April, 1928.

967. Bibliography.—(*See* Explanatory Note, § 58, Vol. 1.)

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Historical Review of Electrical Applications on Shipboard, H. L. Hibbard and W. Hetherington, March, 1925, p. 251.

Electric Propulsion of Ships, W. E. Thau, Vol. 40, pp. 629, 823.

Turbine Reduction Gears *v.* Electric Propulsion for Ships, E. Berg, Vol. 40, p. 724.

MISCELLANEOUS.

Lloyd's Register, which gives annually the latest particulars of electrically-propelled vessels.

The Shipbuilding and Shipping Record (London) describes and illustrates the more important electrically-propelled vessels, as built.

CHAPTER 38.

INDUSTRIAL PROCESSES—CHEMICAL AND METALLURGICAL.

968. Scope of Chapter.—The subjects of electro-chemistry and metallurgy are matters on which specialist treatises must be consulted (*see* Bibliography, § 998). All that can be attempted here is to give a short summary of the main branches of the arts and to point out their importance to the world at large and to the electrical engineer in particular. The Great War caused progress to be made such as would have taken many years to accrue in times of peace, owing to the fact that all ordinary economic sources of supply were for one reason or another either not available or insufficient; also because new alloys with special properties were urgently needed for aeronautical and other war machines. Into the chemical and ionic reactions involved this chapter enters but slightly, but such information as is available is given as to the electrical side of the problem within our limits of space. (For Electric Cutting and Welding, *see* Vol. 2, Chapter 27.)

Of the various industries, some use electricity simply as a source of intense heat in the arc or resistance furnace; others are electrolytic furnace processes; others, again, are electrolytic but involve no furnace; others, again, involve neither furnace nor electrolysis. The successful application of all these processes demands a vast amount of chemical and physical knowledge; the smallest details may be of crucial importance, and they vary widely in individual applications of what is essentially the same process. Many processes are not even patented but are kept secret,* especially in regard to deposition solutions.

The size of, and space required by, the plant, especially where electrolytic cells are involved, are large in proportion to the output

* Just as Courtauld's for long kept the secret of their gas-heated crêpe rollers, on one of which—but a plain one—the writer was detailed to experiment with internal electrical heating. But this was 35 years ago, before induction or eddy current heating came in.

of product, seeing that the raw material is generally in a state of aqueous solution and therefore bulky; but greater purity is obtainable than by other means and very exact regulation is possible. Some processes neither require nor generate any great amount of heat, and so save in maintenance over non-electrical methods; others require far more intense heat than is obtainable by any other means.

969. Cheap Power Essential.—In some of these processes, especially the electro-chemical ones, the cost of power is such a large item in the total cost of the product that it becomes of paramount importance. In these cases it is seldom possible to compete in the world's markets unless water power—and exceptionally cheap water power—is available; by this is meant energy produced and delivered at the industrial factory at an overall cost of not much more than one-tenth of a penny per kWh. It has already been pointed out (Vol. I, § 217) that the capital investment required for water power is generally very high as compared with that for steam power, but that the recurring charges (other than capital), are very low; consequently (apart from the cost of competing fuel) the load factor is the decisive element. In regard to water power, Norway is perhaps in a more favourable position than any other country, though the United States are also fortunate in their hydro-electric resources. Many of these chemical and thermal processes are practically continuous in operation, so that their load factor is between 90 and 100 %. This in itself enables power to be purchased at rock-bottom prices, as the plant is earning its full revenue throughout the 24 hours. Nevertheless, only water power that is distinctly cheap in capital cost can enter the field; a scheme like the proposed Severn Barrage (§ 230, 5th edn.), estimated to produce power for sale at a farthing per unit, is out of the running. Where coal is sufficiently cheap it can give better results than this.

The power factor of an electro-chemical or metallurgical plant is, as a rule, relatively high owing to the large proportion the electrolytic load at unity power factor bears to the total load of the factory; it is therefore seldom necessary to employ means for power-factor correction (Chapter 5). For true electro-chemical processes, *i.e.* those involving electrolysis, D.C. is essential, generally in the form of very heavy currents at low pressure. With modern methods of generation this means that the special generator, or a motor-generator on the public supply, must be used on the

spot, and as near to the work as possible, because of the great cost of the heavy connections. Heating processes may use both D.C. and A.C., but the latter is generally more convenient. In arc furnaces A.C. offers ease of transformation on the spot to any voltage required, and the minimum cost of leads up to the furnace; it also eliminates electrolytic action on the refractory linings, which often become conducting (if not already so) at these extreme temperatures, and in the charge itself. An induction furnace is, of course, essentially an A.C. apparatus, while resistance furnaces may use either A.C. or D.C.

970. Efficiency of Electrolytic Processes.—The weight of a metal electrically deposited from a solution per ampere-second (coulomb) is called the 'electro-chemical equivalent' of the metal. The value of this function is constant for any particular substance, a fact discovered by Faraday, whose name is given to the laws governing these reactions; but different elements have widely different electro-chemical equivalents. Hydrogen has a chemical equivalent of 1 and an electro-chemical equivalent of 0.000 010 38 gramme or 0.010 38 mg. per ampere-second. The weight in milligrammes of any other element theoretically liberated per ampere-second from an electrolyte will be found by multiplying the figure 0.010 38 by the chemical equivalent, or combining weight, of the element. The chemical equivalent is the atomic weight divided by the valency, and in metric units is known as the 'gramme (or gram) equivalent.' Thus silver, which is univalent and has an atomic weight of 107.67, has also a chemical equivalent of 107.67. Its electro-chemical equivalent will therefore be 0.001 118 gramme or 1.118 mg. per coulomb.*

*Faraday's First Law states that where electrolysis takes place, the resulting chemical effect is directly proportional to the product of the current into the time, or to the quantity of electricity which has passed through the electrolyte; and his Second Law states that the weights of different substances deposited or set free at the electrodes are in all cases proportional to the equivalent weights of the substances concerned. Allmand summarises them into the statement 'If a current pass through an electrolyte, bringing about chemical changes at the electrodes, the quantity of each substance formed will be directly proportional to its equivalent weight, to the strength of the current, and to the time of passage of the current' (*Applied Electrochemistry*). The Faraday electrolytic constant, or simply the 'Faraday,' is 96 500 coulombs (nearly) or 26.8 Ah, this being the quantity of electricity required to liberate one 'gramme-equivalent' of the substance—the actual weight, of course, varying with the chemical equivalent and valency.

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The following Table gives the value of these functions for a number of elements:—

TABLE 213.—*Chemical and Electrochemical Equivalents.*

Element.	Valency.	Atomic Weight.	Chemical Equivalent.	Electro-chemical Equivalent in mg. per Coulomb.	Gramme per Ampere-hour.
<i>Electro-positive.</i>					
Hydrogen . . .	H ₁	1·00	1·00	0·010 384	0·037 38
Potassium . . .	K ₁	39·04	39·04	0·405 89	1·459 50
Sodium . . .	Na ₁	22·99	22·99	0·238 73	0·859 42
Aluminium . . .	Al ₃	27·3	9·1	0·094 49	0·340 18
Magnesium . . .	Mg ₂	23·94	11·97	0·124 30	0·447 47
Gold . . .	Au ₃	196·2	65·4	0·679 11	2·444 80
Silver . . .	Ag ₁	107·67	107·67	1·118 00	4·025 00
Copper (cupric) . . .	Cu ₂	63·00	31·5	0·327 09	1·177 00
„ (cuprous) . . .	Cu ₁	63·00	63·00	0·654 19	2·355 00
Mercury (mercuric) . . .	Hg ₂	199·8	99·9	1·037 40	3·734 50
„ (mercurous) . . .	Hg ₁	199·8	199·8	2·074 70	7·469 00
Tin (stannic) . . .	Sn ₄	117·8	29·45	0·305 81	1·100 90
„ (stannous) . . .	Sn ₂	117·8	58·9	0·611 62	2·201 80
Iron (ferric) . . .	Fe ₃	55·9	18·64	0·193 56	0·696 81
„ (ferrous) . . .	Fe ₂	55·9	27·95	0·290 35	1·044 80
Nickel . . .	Ni ₂	58·6	29·3	0·304 25	1·095 30
Zinc . . .	Zn ₂	64·9	32·45	0·336 96	1·213 30
Lead . . .	Pb ₂	206·4	103·2	1·071 60	3·857 80
<i>Electro-negative.</i>					
Oxygen . . .	O ₂	15·96	7·98	0·082 86	0·305 0
Chlorine . . .	Cl ₁	35·37	35·37	0·367 28	1·321 6
Iodine . . .	I ₁	126·53	126·53	1·313 90	4·838 4
Bromine . . .	Br ₁	79·75	79·75	0·828 12	2·980 4
Nitrogen . . .	N ₃	14·01	4·67	0·048 49	0·174 5

In the case of any particular element, the quantity decomposed from its solution per second is proportional to the current. But in practice the full efficiency given by Faraday's Laws is not obtainable. Apart from imperfections in the construction and working of the cells there is often 'local action' (§ 131) as in secondary cells; also in some cases it is difficult to prevent loss of the product as it is formed, *e.g.* sodium. Consequently the 'current efficiency' may vary from about 40 to 100 %. Similarly, the voltage efficiency is always below par, as the actual voltage across a cell must exceed the theoretical 'reversible decomposition voltage' of the substance electrolysed; polarisation and other factors also come into play here. The overall 'energy efficiency' is, of course, the product of the

other two, and therefore lower than either, going down to 20 % or even less in some cases.

Faraday's terms have held good ever since he devised them; the 'anode' is the positive pole of the cell, or the conductor by which the current enters the electrolyte and from which a metal is removed for deposition; and the 'cathode' is the negative pole or that by which it leaves, and on to which a metal is deposited; the 'anion' is the constituent of the electrolyte which moves from the cathode towards the anode, and the 'cation' is that which moves in the opposite direction. The electrolyte itself, where it is divided up by a diaphragm, becomes the 'anolyte' at the anode end and the 'catholyte' at the other. In electro-deposition the cathode is also known as the 'starting sheet' which is built up by electrolysis; consequently it is generally, though not always, of the same pure metal as is to be deposited.

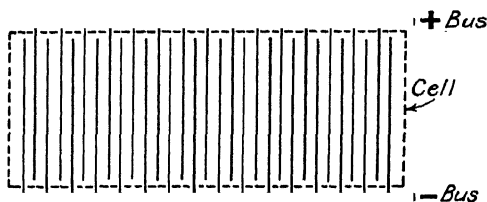


FIG. 413.—Parallel electrodes.

Individual electrolytic cells require very low potential difference, from $\frac{1}{2}$ V to 6 V, so that in practice a number of cells are generally connected up in series to enable generators of standard voltage to be used. Apart from the resistance drop of pressure in the leads and connections from the generator, the actual pressure in any case depends on the theoretical 'decomposition voltage' of the substance electrolysed and on the internal resistance of the cell (§ 21, Vol. 1) including that of the diaphragm between the electrodes, where one is used. For the most part the cells are of large size, requiring currents of the order of 1 000 to 10 000 A, the electrodes being of such size as to give the current density required. This factor, and the temperature at which the cell is maintained, are very important elements in the success of every process. In order to get the large electrode surface generally required, these are normally arranged in parallel groups (Fig. 413),

alternate anode and cathode, like the plates in a secondary battery, an external bus-bar connecting up each set.

A different arrangement, the bipolar electrode (Fig. 414), is used where it is desired to absorb the whole of the P.D. in one or a small number of cells. Here there is an anode at one end of a long cell and a cathode at the other end; in between and face to

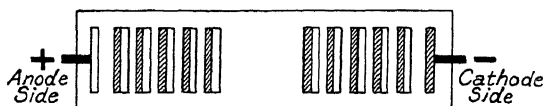


FIG. 414.—Bipolar electrodes.

face are as many bipolar electrodes as are necessary, of which one face acts as the anode and the other as the cathode. The voltage required for the process (called in this chapter the 'pressure per cell') is absorbed at each pair of electrodes, so that a single cell can employ ordinary dynamo voltages.

971. Electric Furnaces.—Electric furnaces fall naturally into two main groups—low- and medium-temperature furnaces, in which the heating element is generally a resistance wire or grid suitably shaped and disposed; and high-temperature furnaces, in which the heating is performed by an electric arc or by the induction of heavy currents in the molten charge itself. In the former class of furnace the ease and accuracy with which electric heating may be controlled is one of its chief advantages; in the latter class the high temperature (up to 3 600° C. or even 4 000°) attainable by electrical means is a consideration of prime importance, compared with the 2 000° C. of combustion furnaces. In all cases the freedom of electric furnaces from contamination by ashes, fumes, etc., is an immense advantage, and they can be regulated so as to have a reducing, oxidising or neutral atmosphere as required. In Chapter 26 (Vol. 2) we have already dealt very fully with the subject of industrial heating generally (§ 634 *et seq.*); with details and illustrations of many types of electric ovens and furnaces (§§ 636, 639, 640); with heating by current conducted into the work (§ 637) and by induced current (§ 638); with induction furnaces (§ 639); with arc furnaces (§ 640); with electrodes for arc furnaces (§ 641); with industrial ovens for various purposes, including melting (§§ 642 to 644); with the properties of metals as to heating and melting (§ 645); with steel furnaces (§ 646); and with melt-

ing furnaces (§ 647). The following Tables in that chapter also bear on the present subject-matter and need not be repeated:—

Table 96A. Electric Ovens, Furnaces, etc., for Industrial Purposes.

*Table 97.** Typical Power and Energy Data for Electrochemical and Metallurgical Processes.

Table 98. Specific Heat, Melting-point, and Latent Heat of Fusion of Materials.

Table 99. Typical Data for Muffle-type Furnaces for the Heat Treatment of Steel.

Table 100. Energy Consumption of Electric Resistance Furnaces.

Table 101. Approximate Consumption of Energy in Melting Metals in Furnaces of 300 to 600 lb. capacity.

Table 102. Morgan Electric Crucible-resistance Furnace.

The above cross-references are given again where necessary in this chapter.

Electric furnaces, heated by resistance coils or grids, are used for laboratory work and in jappanning ovens and other industrial applications; the ordinary domestic oven (§§ 616 to 618; 628) clearly belongs to this class. Various forms of high-temperature electric furnace are used for such work as the manufacture of refractory compounds and for the melting and refining of metals (*see infra*). Electrical energy, for reasons explained in paragraph 622 (Vol. 2) can rarely if ever compete directly with the combustion of fuel as a means simply of producing heat cheaply, and for this reason it is not likely that electric furnaces can ever extensively replace large coal-fired blast furnaces and smelters, though electric smelters of moderate size operate successfully on certain ores and in some other cases where other factors than cheap heat have to be taken into consideration. The chief application of electric furnaces is, however, in the manufacture of special high-grade steels (§§ 976 to 979). In this connection their degree and accuracy of heat control and their immunity from chemical contamination permit results to be secured which can be achieved commercially by no other means.

In arc furnaces (§ 640) the source of heat is an arc struck between two or more large carbon electrodes (§ 641) fed, as

* Erroneously numbered 97A on p. 425 of Vol. 2, 4th edition.

necessary, through the roof of the furnace, and held just above the surface of the molten charge; alternatively the arc may be struck between the electrodes and the charge itself, the second electrode being then a carbon or other conducting block let into the bottom of the furnace. In resistance furnaces (§ 636) for steel manufacture and similar work, two sets of electrodes are plunged into the charge, and the latter is heated by current passing through its own electrical resistance. Currents of several thousand amperes are used in arc and resistance furnaces; hence for convenience and efficiency A.C. supply is employed, step-down transformers are located near the furnace itself, and laminated copper feeders, carrying the heavy low-pressure secondary current, are taken to the furnace terminals. In induction furnaces (§ 639) even these leads are eliminated by building the furnace in ring-trough form, so that the charge itself forms a short-circuited single-turn secondary in which very heavy currents are induced by one or more primary windings connected to the A.C. supply. Owing to heat being produced very close to, or even actually within, the material to be heated in electric furnaces, the thermal efficiency of these is very high—say 60 to 85 % as compared with 30 to 50 % for shaft furnaces; 20 to 30 % for regenerative furnaces; 10 to 15 % for reverberatory furnaces; and 2 to 3 % for crucible steel furnaces. The higher thermal efficiency of the electric furnace goes a long way towards compensating for the more expensive heat employed.

The refractory linings of furnaces always offer difficulties, which are increased in the extreme temperatures of the electric type. They may be summarised as follows:—

Acid Linings.—Silica.

Dinas brick.

Ganister.

Fireclay.

Basic Linings.—Lime.

Magnesia.

Electrically calcined magnesite.

Bauxite.

Neutral Linings.—Carbon; retort or lamp black.

Chromite.

Alundum.

Carborundum.

Chrystolon.

The desiderata in a refractory are: (1) absence of deformation at working temperature; (2) absence of shrinkage; (3) mechanical strength; (4) resistance to the penetration of vapours and slags and to chemical corrosion; and (5) fixity of form and dimensions.

972. Summary of Processes.—Among the more important electro-chemical and electro-metallurgical processes briefly dealt with in this chapter are the following:—

ELECTRIC FURNACE PROCESSES.

(A) *Nitrogen Products.*

Manufacture of calcium carbide and its derivatives, *viz.* cyanamide, ammonia, nitric acid (§ 973).

Direct fixation of atmospheric nitrogen to nitric acid and nitrates (§ 974).

(B) *Metallic Products.*

Electrolytic production of aluminium (§ 975).

The reduction of iron ore (§ 976).

Production of electric steel (§§ 977 and 978).

Production of ferro-alloys (§ 979).

Electrolytic production of metallic sodium and allied metals (§ 980).

(C) *Miscellaneous Furnace Products.*

Manufacture of abrasives; carborundum and silicates; quartz glass (§ 981).

Manufacture of graphite (§ 982).

Distillation products (§ 983).

PROCESSES NOT INVOLVING FURNACES.

Electrolysis of brine (§ 984).

Manufacture of hydrogen and oxygen; ozone; water gas (§ 985).

Other technical chemicals—permanganates, etc. (§ 986).

Electrolytic reduction and refining of copper (§ 987).

Extraction and refining of gold (§ 988).

Extraction and refining of silver (§ 989).

Extraction and refining of nickel (§ 990).

Zinc extraction (§ 991).

Lead refining (§ 992).

Tin recovery (§ 993).

Electro-plating and electro-typing (§ 994).

§ 973 ELECTRICAL ENGINEERING PRACTICE

In his Presidential Address to the Institute of Chemical Engineers * Sir Alexander Gibb gave the following figures of power required, and output:—

Pulp and paper . . .	1 800 to 2 000 kWh per ton.
Hydrogen . . .	1 600 kWh per 1 000 cu. ft.
Pig iron . . .	2 000 to 3 000 kWh per ton.
Electrolytic zinc . . .	3 800 to 4 000 „
Calcium carbonate . . .	4 000 to 4 500 „
Direct synthetic nitrogen . . .	5 000 „
Ditto, with arc process . . .	80 000 „
Nitrogen by cyanamide process . . .	20 000 „
Ferro-alloys, various . . .	5 000 to 15 000 „
Phosphorus . . .	11 000 to 15 000 „
Magnesium . . .	18 000 to 20 000 „
Aluminium . . .	25 000 „

He also pointed out that the world's consumption of aluminium is 400 000 to 500 000 tons a year, involving $2\frac{1}{2}$ million H.P., which at 0·1d. per unit is 20 % of the cost of the product; for pig iron, energy at the same rate costs 30 % of the present-day price of the metal. Reference may also be made to the 'Review of Progress' † under the sub-head 'Electrolytic Extraction and Refining of Metals.'

ELECTRIC FURNACE PROCESSES.

A. Nitrogen Products.

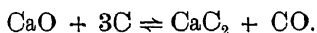
973. Nitrogen Products.—A great deal of useful information regarding the processes summarised below is to be found in the Report of the Nitrogen Products Committee of the Ministry of Munitions, 1919. Using coal, the Committee estimated that a 100 000 kW power station could be equipped at a cost of £10·26 per kW and that the 'works cost' of energy, exclusive of interest and depreciation, would be £3·75 per kW year at the switchboard with coal at 7s. 6d. per ton. Such a price, or anything approaching it, is unlikely to occur in future however, except at the pit's mouth. The report assumes that 1·87 kW years are required per metric ton of 100 % nitric acid produced by the arc process, equivalent to 8·4 kW years per metric ton of fixed nitrogen. On these (now no longer tenable) data the cost of production of calcium

* *Elec. Rev.*, Vol. 102, p. 618.

† *Jour. I.E.E.*, Vol. 66, p. 550.

and sodium nitrate would be £0·58 and £0·60 per metric ton of fixed nitrogen. By the cyanamide process the Report estimates the cost as £0·24 per metric ton of fixed nitrogen in the cyanamide; £0·29 when in the form of ammonia liquor; and £0·38 in the form of ammonium sulphate; all on the same basis of fuel cost. Plants for the manufacture of nitrogen products are in operation in the United States, Great Britain, Germany, France, Scandinavia, Italy, Japan, Korea and Brazil. The 'Review of Progress' in the *Journal of the I.E.E.*, Vol. 66, p. 537, also gives much useful information on all these processes.

(1) *Carbide of Calcium*.—Various types of electric arc furnace (§ 640) are used in the manufacture of calcium carbide, from which acetylene, cyanamide and many other derivatives are obtained. The process is carried out on a large scale at the British-owned works at Odda, Norway, and at many other places throughout the world. There are two types of furnace, each with variations, according to whether the container is used as one electrode with the other suspended above it or both electrodes are above the container. There are also two methods of drawing off the finished product, either as a solid ingot or, more recently, as a liquid tapped off through the side of the container. The raw materials used are freshly burnt quick lime and anthracite coal, charcoal or coke, free from phosphorus and sulphur, in the proportion of 1·7 to 1, and the reversible reaction which takes place is

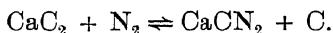


The process depends on the high temperature obtained, about 3 000° C., so that a very large current at low pressure is used; the arc may be either single-phase or 3-phase. Single furnaces have been constructed for as much as 10 000 kW and the yield is between 3 000 and 4 500 lb. of 80 % carbide per kW year, according to the type of furnace used.

(2) *Acetylene*.—This gas, formed by the action of water on calcium carbide, is merely mentioned because the present carbide industry arose entirely on the false hopes generated (along with the gas) in the early days of manufacture, when it was imagined—under the influence of the company promotor—that it would displace all other illuminants. At present, except for use in cycle lamps, most of the gas made is utilised in the oxy-acetylene jet for

metal cutting, where electric cutting (Chap. 27) now actively competes with it.

(3) *Cyanamide*.—When calcium carbide is heated in pure nitrogen, the valuable fertiliser calcium cyanide (also called cyanamide; lime nitrogen; nitrolim) is formed according to the reversible reaction



Pure nitrogen is obtained in the ordinary way, by the fractional distillation of liquid air; and this is passed into retorts containing powdered carbide. The heat is obtained from the reaction itself after it has begun, but it is started by the electrical heating of a carbon rod in the mixture. The yield is about 1 000 lb. of fixed nitrogen (or 5 000 lb. of cyanamide) per kW year.

(4) *Ammonia*.—From cyanamide, ammonia can be obtained directly, by the action of superheated steam. Synthetic ammonia is also produced by the direct combination of its elements, by the Haber process. The reaction is exothermic, that is one evolving heat, and a low temperature therefore assists it. The hydrogen and nitrogen are circulated under a pressure of about 200 atmospheres over a catalyst such as osmium or uranium, contained in an electrically heated tube maintained at about 500° C., and thereafter through fine tubes maintained at a very low temperature. The ammonia liquifies and the unchanged residue is re-circulated. The Nitrogen Products Committee states that whereas the highest yield previously recorded was 1 kg. of ammonia per hour per litre of space occupied by the catalyst Dr. Harker obtained from 10 to 20 kg. at working pressures of 100 to 150 atmospheres.

In connection with ammonia plants there is also the manufacture of ammonium nitrate and carbonate and of nitro-chalk; and at the works of Imperial Chemical Industries (Billingham) ammonium sulphate is made, using natural anhydrite mined on the spot in place of sulphuric acid.

In addition to the Haber process ammonia is also made by the Carrara, the Fauser and the Casale; and the Claude process is coming into extensive use, in which the nitrogen is first liquefied for the elimination of oxygen and then compressed, with three times its volume of hydrogen, to 800 atmospheres, after which it is brought into contact with Casale catalysts at a temperature of 500° C.

Yet another process for obtaining ammonia is that of Serpek, in which bauxite is heated in an electric furnace with coal, in an atmosphere of nitrogen, when the reaction



gives aluminium nitride. This is decomposed by boiling with caustic alkali to form ammonia and sodium aluminate, from which pure Al_2O_3 can be recovered.

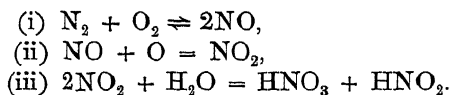
(5) *Nitric Acid*.—In its turn, by the Ostwald process, ammonia can be oxidised, in the presence of a suitable catalyst such as platinum, to nitric acid. This reaction can be so regulated that only about half the ammonia is converted into acid, the remainder being then neutralised by the acid already formed so as to give ammonium nitrate; this is extensively used in the manufacture of high explosives.

It is impossible here even to mention all the nitrogen products of the present day, which are constantly added to; some of them are extensions of those dealt with above or are inter-connected with the nitrogen produced by direct fixation (§ 974). The value of phosphorus (§ 983) as a fertiliser has led to its combination with nitrogen products in the form of Nitrophoska, or nitrogen-potash-phosphoric acid fertiliser, made at the Leunawerke in Germany; this is produced from chloride of potassium, nitric acid and phosphoric acid, the production (1928) being 120 000 tons a year. Similar fertilisers are Leunaphos (N 29 % : P_2O_5 15 %) and Diammonphos (N 19 % : P_2O_5 15 %).

974. Direct Fixation of Atmospheric Nitrogen.—The natural sources of nitrates in bulk, namely, saltpetre and Chili saltpetre, have long been insufficient even for the world's agricultural needs; and they proved not only inadequate but also unprocurable during the war, when they were required as the source of nitric acid in the manufacture of explosives. Until special factories were hastily erected and equipped during the struggle the chief sources of synthetic nitrates were the factories at Notodden (§ 219) and Rjukan (§ 243) in Norway, where some 300 000 H.P. is developed at various points on a single river for this single industry. Later on many other factories were started, some using water power and others steam power.

(1) *Birkeland-Eyde Process*.—The direct oxidation method of Birkeland and Eyde is employed at the Rjukan group of factories

in Norway. Each 3-phase 50-cycle generator of 10 000 kW serves its own bank of three separate high-pressure single-phase star-connected arc furnaces, consisting of a steel casing lined with refractory material. The air is drawn into the narrow space between the linings through multiple holes in the centre, and is discharged at the circumference after treatment. At the centre the arc is formed between hollow water-cooled $2\frac{1}{2}$ -in. copper tube electrodes about $\frac{1}{2}$ in. apart. Clearly such a short arc would amount practically to a short-circuit, and the high pressure could not be maintained across it even in a strong outward current of air. A powerful electro-magnet is therefore so arranged that its repulsive effect is directed on to the arc and spreads it outwards into a fan. Thus the pressure is maintained between the electrodes, and a succession of separate arcs are started which, being A.C., are broken at each half-cycle. Practically the whole of the narrow cylinder between the walls, some 6 ft. in diameter, is therefore a mass of nitrogen burning in oxygen. Unlike most combustion processes, which when once started are self-supporting, the oxidation of nitrogen is endothermic, *i.e.* it takes place with absorption of heat, the higher the temperature of the gases the greater is the amount of nitric oxide produced. The actual percentage oxidised is small, some $1\frac{1}{2}$ to 2 %, probably due at least in part to the fact that the reaction is a reversible one. The product, nitric oxide, NO, leaving the furnace, must be very rapidly cooled to prevent it splitting up again. Regenerative steam boilers absorb most of the heat, which thus reappears in the form of additional power; the equivalent of one ton of coal is recovered in this way per kilowatt-year expended in the furnaces, and the yard locomotives are operated by thermal storage boilers so supplied. In the course of cooling the NO is further oxidised to nitric dioxide NO₂. This is passed up through a succession of concentrating towers loosely packed with quartz, meeting water (or dilute acid as the chain proceeds) on the way down, with the result that a mixture of nitric and nitrous acid is formed. The residue of gases is then absorbed with caustic soda and gives sodium nitrate. The equations of the process are



The final product is generally nitrate of calcium (Norwegian saltpetre), the acid being neutralised by limestone or lime and concentrated by evaporation. Each arc has a choking coil in series with it, reducing the pressure from about 5 000 to 4 000 V. The overall power factor of the system is low, from 0·65 to 0·7. Some 1 300 up to 2 000 lb. of nitric acid are obtained per kW year.*

(2) *Schönherr and Pauling Processes*.—These are also single-phase high-pressure arc furnaces, in which the reactions are the same while the constructional details are different. In both the air is pre-heated regeneratively, and the current of air alone spreads the arc, without any electro-magnetic device. The Schönherr furnace is tubular in form, and the arc is practically a continuous one of great length between an electrode at the base and the containing tube, up which the air carries the flame. The Pauling arc is formed between horns such as are used in the common form of lightning arrestor, and is struck afresh, like that in the Birkeland-Eyde furnace, at each reversal.

(3) *Other Processes*.—Mention may also be made of the Moscicki-Kowalski, the Wielogaski and the Island furnaces.† In the Kilburn-Scott furnace, as described by the inventor,‡ a 3-phase arc is used, giving greater continuity, as there is no moment in which more than one arc is extinguished at the zero line. The percentage yield is consequently said to be higher than with single-phase furnaces, to the extent of about 50 %. None of these have, however, come into extensive use.

B. *Metallic Products.*

975. Aluminium.—The electric furnace, coupled with the development of water power, has created a huge industry in the manufacture of aluminium; for, though it is one of the commonest constituents of the earth's crust, it was previously only obtained with difficulty and at great cost by the process of separation with metallic sodium. The writer can recollect handling a precious sample in the school laboratory when it was far more expensive than silver! Alloys of the metal were first produced electrically

* The specific energy consumption in the arc process is 73·7 kWh per kg. of fixed nitrogen, or 250 lbs. per kW year. See 'Electrochemistry and Electrometallurgy,' by W. E. French, *Jour. I.E.E.*, Vol. 66, p. 537.

† Described in *Jour. I.E.E.*, *loc. cit.*

‡ *El. Rev.*, Vol. 86, p. 681.

from emery, by the Cowles furnace, but this method has long been superseded.

In recent years bauxite has replaced all other raw materials as the source of aluminium; it consists of hydrated alumina with silica and iron in varying proportions, but in the best deposits the alumina accounts for between 60 and 70 % of the total. If this admixture were used in the furnaces—as it was in the early days of the industry—the product would be an alloy. In order to obtain metallic aluminium by the electrolytic processes of Héroult and Hall, it is first necessary to obtain, by purely chemical process, practically pure aluminium oxide or alumina Al_2O_3 by separating it from the iron and silicon impurities. The metal is then obtained by the electrolysis of a solution of the pure alumina in fused fluor spar (calcium fluoride) and cryolite, which is a sodium-aluminium fluoride. An iron crucible lined with carbon (which must be of the purest) is used initially as a cathode, until the metallic aluminium produced sinks and acts as the cathode, with rods of carbon as the anode. Each crucible requires from 6 to 7 V and the current may be as much as 10 000 A. As the metal is produced it sinks to the bottom and is tapped off, the heat produced by the passing of the current being sufficient to keep the mass in a molten condition. At the anode CO_2 is given off.* A kW year produces about 800 to 860 lb. of aluminium (Table 97, Vol. 2).

976. Reduction of Iron Ore; Refining Iron.—(1) *Reduction.* The modern blast furnace has a high thermal efficiency, as the waste gases from them can be, and generally are, utilised for steam generation or in gas engines, after being passed through a second time for reheating the mixture. Where the deposits of ore and coal (for coke) occur together, the method holds its own; but where rich deposits of ore are far from coal supplies, and cheap power—especially water power—is at hand, the electric furnace has the advantage. Consequently, Great Britain is somewhat behind Scandinavia, Italy, Canada and California in this industry. The ease with which the temperature of the process can be exactly controlled, and the high quality of the pig iron are both factors favouring the electric process; but price is the determining factor. Although developed later in point of time than the other ferro-industries, the electric

* Useful information on the subject will be found in articles in *Engineering* for August 16 and 23, 1918, as well as in many other papers. See also the 'Review of Progress,' *Jour. I.E.E.*, Vol. 66, p. 537.

reduction of iron ore is now a commercial process in places where power is sufficiently cheap. As is well known, the greater part of the fuel—two-thirds—used in a blast furnace is consumed merely in order to supply the necessary heat to the ore, the flux and the air in the blast; only a comparatively small amount is required for the reduction process itself. If therefore the heat is supplied by means of electricity, at a rate sufficiently cheap, the use of the extra fuel, with its ash and other impurities, are avoided. Electric reduction is employed at the State-owned power station on the Trollhätten falls and elsewhere in Sweden; at Sault Ste. Marie, Ontario; at Héroult, California, and in Italy. In various other parts of the world the adoption of electric reduction probably only awaits a fuller investigation of water-power resources. At the present time single furnaces are working up to 8 000 H.P., and the limit of capacity is mainly a matter of the size of electrodes obtainable. In the smaller furnaces three electrodes were used, but now as many as twelve are employed by Electro-Metals, Ltd. The general arrangement of the electric furnace is not dissimilar to that of a blast furnace, but the shaft is not so high. Either coke or charcoal may be used as a reducing agent, and the design is different according to which is available; for the flux, limestone is used, and less is required in the electric furnace than in the blast owing to the smaller amount of ash produced. It follows also that the waste gases have a higher calorific value than blast-furnace gases, the percentage of CO being greater. The gas is re-circulated through the mixture in order to re-heat it before its residue is drawn off for other purposes. The electric supply to a reduction furnace is 3-phase^{*} current transformed down to a low pressure, capable of variation between 35 and 100 V and subdivided at the transformer so as to give 3, 6 or 12 phases in effect according to the number of suspended electrodes. The power factor is from 0.92 to 0.95. The yield is from 3 up to 5 tons per kW year (according to the ore used) and the annual load factor is over 82 %. From the amount of fuel saved it follows that the electrical furnace can compete on cost with a blast furnace when one H.P. year costs less than the 2 tons of fuel saved; Mr. W. E. French^{*} states that 'comparative figures worked out on definite assumptions for both

^{*} 'Electricity in Ferrous Metallurgy.' *The Times Trade and Engineering Supplement*, Nov. 19, 1932.

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systems, irrespective of their metallurgical advantages and disadvantages, show that the electric furnace can just compete with the blast furnace when 1920 kWh cost less than 0·7 ton of coke. Furthermore, the pig iron contains less phosphorus and sulphur and is therefore of a higher quality. Among the furnaces used are the Stassano (§ 640), the Keller, the Tinfos or Lorentzen, the Hérault (§ 640) and the Electro-Metals (§ 640).*

(2) *Refining*.—The shortage of copper during the war caused attention to be given to other metals for use as conductors, and even insulated iron wire was extensively used. Iron is used to some extent in electro-typing (§ 994), where it is deposited from a strong solution of ferric chloride with sodium (or calcium) chloride. The electrolysis both for this and in other cases is carried out at a high temperature, in order to get pure ductile iron, and the process is used in the production of the metal for special purposes—including transformer cores. Pure iron electrodes are used, and very exact regulation of the acidity is necessary in order to avoid, on the one hand, brittle deposits, and on the other, basic precipitates.

977. Electric Steel from Arc Furnaces.—While fuel costs are the crux in electric smelting, this is not so with electric melting and mixing, as required in the manufacture of the highest grades of tool steels, etc. In the older but still generally used method of making ‘crucible steel,’ high-grade raw material is used, and the product shows virtually an average analysis of what is charged into the crucible, simply amalgamated with the minimum of chemical change. Electric furnaces of the types dealt with in this and subsequent paragraphs are largely replacing both the crucible and open hearth processes for tool steels and also alloys and stainless steels (§ 979). The heating is capable of exact temperature regulation and is quite independent of the nature of the charge, and the metal bath can be left neutral or be made oxidising or reducing at will, according to requirements. Sometimes open-hearth steel is transferred directly into the electric furnace for finishing. During the war the electrical production of high-grade steel made great strides, because of the perfect control which is possible in the operation. As the whole of the heat required is supplied electrically,

* ‘The Electrometallurgy of Iron,’ in the ‘Review of Progress,’ *Jour. I.E.E.*, Vol. 66, p. 542.

the introduction of impurities due to fuel is avoided, and even low-grade raw materials can be worked up into high-grade steel. For the most part the raw material used is scrap steel, from which the finest crucible steel is then produced; but pig iron, run directly in from the reducing furnace, is also used to make steel of the open hearth variety. Single-phase, 2-phase and 3-phase arc furnaces (as described and illustrated in Vol. 2, § 640) are variously employed, generally with electrically produced graphite electrodes (Vol. 2, § 641) which consume at the rate of about 22 lb. per ton of steel. The power required in the larger sizes varies from 150 to 250 kVA per ton capacity, and the power factor varies between 0·8 and 0·9. The best-known types of arc furnace are illustrated in paragraph 640 (Vol. 2) as follows: Stassano (Fig. 224), Rennerfelt (Fig. 225), Booth (Fig. 226), Hérault (Fig. 227), Girod (Fig. 228), Electro-Metals (Fig. 229), Greaves-etchells (Fig. 230), and Stobie (Fig. 231). The present sizes range from an output of one-half up to 15 tons of steel per heat, and the working period is from 4 to 8 hours per heat, the power consumption being from 1 200 to 700 kWh per ton of steel, of which roughly half is saved when the charge is run in molten.*

978. Electric Steel from Induction Furnaces.—(1) *Low-frequency.*—In the induction type of furnace (Vol. 2, § 639), due originally to Ferranti, the charge of raw material is arranged in a circular trough or a figure-of-eight which is made the closed secondary circuit of a transformer with a single turn only (Figs. 217, 218, Vol. 2); thus the current in this coil of molten metal may be of the order of 20 000 to 30 000 A in a comparatively small furnace. There is an automatic circulation of the molten mass, due to the ordinary electro-magnetic tendency of the coil to enclose the maximum flux in spite of the gravitational endeavour to keep the surface flat; and there is also a rotation around the ring following the magnetic field; these effects ensure very thorough mixing of the charge and improve the quality of the product. A limit to the current which can be used is set by the pinch effect (§ 639, Vol. 2) due to the mutual attraction of neighbouring rings of metal carrying the current in the same direction, although actually in contact; if the distortion becomes great enough to break the circuit it may be difficult to restart it satisfactorily without much loss of time. Both

*See also 'The Electrometallurgy of Steel,' *Jour. I.E.E.*, Vol. 66, p. 545, where useful tables will be found.

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single-phase and 3-phase induction furnaces, at 15 to 25 cycles, are in use, and the yield is similar to that of the arc furnace. The power factor is, of course, lower, namely, from 0·5 to 0·8 only. The best known types are the Ajax-Wyatt (Fig. 222, Vol. 2), the Kjellin and the Röechling-Rodenhauser (Figs. 219, 220, Vol. 2).

(2) *High-frequency*.—Frequencies from 500 to 2 000 cycles per sec. are used in the high-frequency furnace, according to the design and the charge, motor-generators being used for the necessary conversion. Here again the product is the arithmetical sum of the materials in the charge, which cannot take up sulphur, as it does when coke is used, or carbon, as in an arc furnace. The efficiency, for reasons stated below, is much higher than that of an arc furnace; it is stated* that 'based upon the average rates for electric supplies in industrial districts, steel superior in quality to the best crucible steel is manufactured at approximately half the cost'.

The Ajax-Northrup high-frequency induction furnace (Vol. 2, § 639 and Fig. 223) is also used in the production of crucible tool steel, by Messrs. Edgar Allen & Co. of Sheffield.† This is said to be the 'first of its kind in the world to be used commercially for the manufacture of high quality tool steel.' The capacity is 450 lb. per filling, taking one hour (= 20 tons a week), and the current consumption remarkably low, because the heat is generated exactly where it is wanted, inside the metal, and not outside as in the older crucible methods. In place of the secondary channel of the ordinary induction furnace, eddy currents are induced in the steel itself, before and during melting, in a centrally placed crucible, a helical inductor coil surrounding the furnace bath. The supply frequency is 2 200 cycles and the pressure is 1 200 V; for operating it a 150 kW motor-generator set is installed, running off the town mains at 230 V, 50 cycles, 3 000 r.p.m. As the power factor of the furnace is very low, and varies with the temperature, a fixed and a variable (regulating) condenser are connected in parallel with the furnace coil. The eddy currents cause a very rapid rotation of the molten metal in the vertical plane, causing appreciable curvature on the surface.

978A. Heat Treatment of Steels; Resistor Furnaces.—The steels produced from the various types of electric furnace

* W. E. French, *Loc. cit.*, § 976.

† *The Times*, Dec. 7, 1927; *El. Rev.*, Vol. 101, p. 1029.

described, or from non-electrical types, often require subsequent heat treatment in order to obtain definite qualities in the finished product, such as hardness, annealing, temper or carburisation. For these purposes temperatures from 500° to 1 000° C. are required,* and are obtained by external radiation from Resistor furnaces (*see also* § 636, Vol. II) instead of internally. The elements in this furnace consist of spirals of nickel-chrome wire, carried by special refractory supporting brickwork—like a large domestic fire. The brickwork is assembled inside sheet-steel casing and forms the inner radiating surface of the heating chamber of the furnace into which the charge is placed. In order to prevent heat losses by radiation to the exterior, the outer walls are well lagged with heat-insulating material, and the doors are designed to minimise the escape of heat.

979. Ferro-Alloys and their Steels.—There are numerous alloys of both iron and steel with the rarer metals which impart special qualities. Steels which, in addition to carbon, have added to them a proportion of some other metal, or of more than one other metal, are classed as ternary or quaternary ferro-alloys; there are many of these, and in each of them the proportion of added metal may be greatly varied in order to give alloys of widely differing properties. In the early experimental work the rare metal actually required was added in metallic form to the iron or steel; but the high melting-point of most of these alloying metals created difficulties. The modern practice is to form ferro-alloys from iron and convenient compounds of the rarer metals, and very rich in those metals, and then to add the required amount of the alloy so made to the steel in order to obtain the desired percentage of the rarer metal. Care must therefore be taken to distinguish between the first rich product of iron alloy and the subsequent final alloy steel with only a small proportion of alloy. These alloys are produced both by the 'Thermit' and blast-furnace processes—purely thermal—and in the electric furnace, the latter giving the more perfectly controlled results and the higher quality product.

The production of a ferro-alloy with a low carbon content or a high percentage of the alloying element is limited in the blast furnace by three difficulties. First, the temperature is too low for the reduction of some of the oxides of the alloying metals, so that

* W. E. French, *loc. cit.*, § 976.

only alloys of metals reduced at a comparatively low temperature or of low melting-point can be made; secondly, it is difficult to obtain an alloy containing a high percentage of the alloying metal; and, thirdly, it is impossible to produce a ferro-alloy low in carbon because of the great excess of carbon in the charge.

The best-known ferro-alloys are enumerated below; but new ones, or old ones in new proportions, are constantly being added to the already formidable list. The power consumption per ton, the power factor of the processes, the electrode consumption and similar working details vary considerably with the type of furnace used and its size; generally the kWh / lb. figure is lower as the weight of charge increases. The data in Tables 214 and 215 are compiled from American sources.* Presumably the short ton (2 000 lb.) is implied.

TABLE 214.—*Power Consumption and Raw Material for some Ferro-alloys.*

Product.	Per Ton of Manufactured Product.		
	kW-day (24 hours).	Raw Material Handled. Tons.	Tons Raw Material Handled per kW-year.
Ferro-silicon, 50 % . .	300	3·0	3·3
" 80 % . .	650	4·0	2·0
" 10-12 % . .	109	1·55	4·7
" 25-30 % . .	172	1·90	3·65
Ferro-chrome, 8 % . .	360	4·0	3·7
Ferro-molybdenum . .	360	3·5	3·2
Ferro-tungsten . .	325	3·0	3·0

(1) *Ferro-Silicon*.—With a low silicon content, up to 15 %, ferro-silicon is a blast-furnace product; above that percentage it is mostly made in the arc furnace. The carbon figure is generally low, since iron has a greater affinity for silicon than for carbon. Sulphur is generally low, owing to the process of manufacture, but phosphorus is not removed in the smelting operation. The charge consists of iron—often turnings—or steel, with quartz or sand and either charcoal, coal or coke. Iron ore may be used instead of W.I. turnings, but this increases the energy consumption; C.I. turnings and borings introduce phosphorus. For the higher grade

* *Electrical World*, July 24, 1920.

TABLE 215.—*Kilowatt-hours per Lb. for some Ferro-alloys.*

Product.	Tons Charged.	kW.	Type.	Recovery.	kWh per Lb. Alloy Tapped.	kW-day per Ton.
Ferro-silicon, 50-70 %	3-4	1 000	1-ph.	—	2·5-3	233-280
Ferro-manganese, 75-80 % Mn	15	1 200	3-ph.	70-85	2-2-3	205-280
Ferro-chrome, 60-65 % Cr, 4-6 % C	13-15	750	3-ph.	70-80	3-4-5	280-420
Ferro-tungsten, 70-75 % W	0-75	150	1-ph.	80-90	{ 2·1 Sm't 1·7 Ref'n	190-354 158
Ferro-molybdenum, 60-65 % Mo, 15-20 % C	—	150	1-ph.	78-80	7-7·5 (per lb. Mo)	650-700
Ferro-vanadium, 30-35 % Va, 3-4 % Si	1	150	3-ph.	75 av.	3-4	316
Ferro-uranium, 35-50 % U, 3-4 % C	800 lb.	75	1-ph.	75	3-5	325

products (75 % Si and upwards) charcoal is used, with 80 % reduction. The silicon content varies from 10 to over 95 %. The energy consumption is said to be—

25 % Si alloy, 1·8 kWh per lb.

50 % " " 3·6 " "

75 % " " 5·4 " " (cf. Table 215).

Electrode consumption is about 80 lb. per ton. The alloy is used especially as a reducing agent in the manufacture of steel and steel castings, when it passes into the slag; but it is also used for adding silica to steel in the cupola, to the extent of 1 to 5 %. Hadfield's *silicon steel* has a higher magnetic permeability than the purest iron, and is therefore much used in place of the latter where this property is of value. It is known that 30 to 70 % ferro-silicon is liable to disintegration, and, if damp, may produce poisonous gases due to the presence of Ca_3P and CaC_2 .

(2) *Ferro-Manganese*.—This, in the lower grades, is still for the most part a blast-furnace product, and the alloy is often present in the iron ore; in the higher grades it is smelted from manganese ores or with manganese dioxide, with carbon (anthracite) as a reducing agent. In the high temperature of an arc furnace the manganese is apt to volatilise, and no open arc should be allowed to form; the smelting zone should be entirely buried in the charge to prevent this. Ferro-manganese is now made successfully in resistance furnaces, and then contains much less carbon than the older

product. This ferro-alloy is largely used for making silico-manganese (*infra*). It is also used for the deoxidation and recarburisation of ordinary Bessemer and open-hearth steel. The power consumption varies considerably with the furnace, but in a 1 000 kW unit it is about 7 000 kWh per long ton and, in a 3 000 kW unit, about 4 000 kWh. In a 1 200 kW furnace in Colorado the actual figure was 6 500 kWh per long ton. *Manganese steel* is also made by suitable addition of the alloy, and generally contains 12 or 13 % of manganese and $1\frac{1}{2}$ to 2 % carbon. In these proportions it is extremely hard and yet not brittle, whereas with much less alloy it can be powdered under the hammer.

(3) *Silico-manganese*.—The two alloys just dealt with are sometimes combined to form silico-manganese (or ferro-manganese-silicon) in the electric furnace; but it is more economical to smelt manganese ores and quartz or else Rhodonite. The melting zone should be well covered with the charge. In a 3 000 kW furnace the consumption is 5 400 kWh per ton, and the electrode consumption is high—up to 200 lb. per ton. The percentages of the added metals vary greatly, but the carbon content is always low. Apart from its use in deoxidising steel, the alloy is used for making *manganese-silicon steel*, for which purpose it is added just before tapping or even in the ladle.

(4) *Ferro-tungsten*.—For this alloy wolframite or other tungsten ore or concentrate (60 %) is added to the iron and reduced in the arc furnace; and the product contains from 50 to 80 % of tungsten. It is generally made in a small 150 kW single-electrode furnace, which is broken down to remove the smelted mass, which is afterwards refined. An excess of carbon is used, to prevent loss of tungsten into the slag. The first smelt, with carbon and flux, gives a product containing 3 % of carbon; this is then re-smelted with an oxidising slag to obtain a lower carbon alloy. The energy consumption is, for smelting, 3 kWh per lb. and, for refining, 2 to 4 kWh. The alloy is used for making *tungsten steels* of the self-hardening class, as used for high-speed tools; and also armour plate and the like. Tungsten steel also has special properties for making permanent magnets which are to be subjected to great heat, when it retains its magnetism better than plain carbon steel.

(5) *Ferro-chrome*.—This alloy is made by the reduction of chromite, which is composed of oxides of chrome and iron with many impurities. The proportion of chrome in the initial alloy

varies greatly, but is generally over 50 % and usually from 60 to 65 %. The silicon and carbon content also are very variable, but the latter generally amounts to 5-10 %. The energy consumption in the process is about 3 kWh per lb. The high-carbon ferro-chrome is decarburised and the finished product is added to steel to the extent required. *Chrome steel* used for armour plate and projectiles contains about $1\frac{1}{2}$ % chromium, $3\frac{1}{4}$ % nickel and 0.25 % carbon; and the ferro-alloy added in the making contains a high percentage both of silica and carbon. High-speed tools and castings are also made from chrome steel, while 'stainless steel' is a homogeneous ferro-chrome of low carbon content; the popular idea that it is a form of case-hardened iron, and that stainless knives cannot be sharpened in the ordinary way, is of course erroneous.

(6) *Ferro-molybdenum*.—This alloy is made in the resistance furnace from iron and the sulphide ore molybdenite, with from 50 to 85 % molybdenum. The alloy is added in definite proportions to make *molybdenum-steel* in the electric steel furnace, where a smaller amount of it gives much the same properties as a larger amount of tungsten. A small percentage of this metal greatly increases the elongation and elastic limit of steel. Chrome is sometimes used in combination with molybdenum.

(7) *Ferro-nickel*.—Though usually made by the direct admixture of the metals in the crucible, ferro-nickel is also produced in the electric furnace. The ore is first roasted and then smelted in the furnace to give a pig iron containing 2 % Ni and 0.4 % Cu, from which *nickel steel* is then made by Bessemer process. It is valuable for use as resistance wire, owing to its non-rusting properties and freedom from corrosion generally. Mention may be made also of the series of nickel-iron alloys, with ± 5 % of copper and a little manganese, known as 'mumetal'; these alloys, with a magnetic permeability of some 7 000, are used for the conductors of submarine cables, giving a 7- or 8-fold increase in working speed. High-frequency melting (§ 978) was first used in Europe in this connection.*

(8) *Ferro-aluminium*.—This alloy, containing from 5 to 20 % of aluminium, is made by plain mixing and melting in the electric furnace. Like so many of the others, it is used in deoxidising steel.

* Carpenter, *Proc. Inst. C.E.*, Vol. 224, p.

(9) *Ferro-boron*.—This is made by the reduction in an electric furnace of coemanite and iron, with carbon, and contains about 10 % of boron. The alloy is mostly used for desulphurising and deoxidising steel; but tempered *boron steel* itself, with $\frac{1}{2}$ % of boron, has great tensile strength and resistance to shock.

(10) *Ferro-phosphorus*.—Considering the trouble that the elimination of phosphorus causes in ferro-metallurgy, it seems strange that it should be deliberately introduced; but this alloy is made from apatite, in the electric furnace, and when added to steel in the correct proportions gives it good rolling properties for making tin-plates.

(11) *Ferro-Vanadium*.—This is used in the production of vanadium steels, and is made by reducing vanadium oxide with silicon. The crude product contains from 30 to 35 % of vanadium and from 3 to 6 % of silicon; on refining, the silicon content is lowered to 1 % and the carbon to 0.5 %.

(12) *Ferro-Uranium*.—This is used for increasing the hardness and toughness of steel. The proportions vary from 25 to 50 % of uranium; from 1.5 to 4.5 % of carbon; and from 1 to 4 % of silicon. For the high-carbon product small electric carbon-lined furnaces are used, with two electrodes, and a consumption of 600 to 750 A at 60 to 90 V. The recovery is 85 % with energy consumption of 6 kWh per lb.

The low-carbon product, with about 2 % carbon, uses a carborundum-lined furnace with water-cooled hearth and requires from 3 to 4 kWh per lb.

(13) *Ferro-Titanium*.—This is employed to remove both oxygen and nitrogen from steels; the composition varies considerably, high-carbon alloys containing from 15 to 18 % of titanium, while the carbon-free alloy is made by the Thermit process. Titaniferous ores are reduced in the electric furnace or with aluminium, as the case may be. Titanium oxide in the steel, in the form of small particles, is objectionable; so silico-titanium is generally used, as the oxide is more fusible in the presence of silicon.

(14) *Other Ferro-alloys*.—Smaller amounts of *ferro-zirconium* and *ferro-tantalum* are also made in the electric furnace, as well as an ever-increasing list of new binary, tertiary and multiple steels from combinations of those ferro-alloys dealt with above with suitable steels. The field for many of these is enormous when the price becomes lower.

980. Sodium and Allied Metals.—The metals sodium, potassium, calcium and magnesium are all now produced electrolytically from their fused salts, in the electric furnace, somewhat after the manner of aluminium.

(1) *Sodium and Potassium.*—Sodium is obtained by electrolysis of fused sodium hydrate, with carbon anodes and iron cathodes (Castner and others); of a fused mixture of sodium hydroxide and carbonate (Becker); of fused sodium nitrate (Darling); and of fused sodium chloride (Ashcroft). The metal rises in globules to the surface, and is removed thence as it forms. The current efficiency is about 45 % only, as the water formed at the anode during the process combines with some of the metal; and even this figure falls unless the temperature is kept as low as practicable. The cells take about 500 A at $4\frac{1}{2}$ V, as against a decomposition voltage of 2.2 V; so the energy efficiency is only 22 %.

Potassium also was first isolated, along with sodium, by these means, by Sir Humphry Davy in 1807; but the demand for it is small. A kW-year produces about 1 600 lb. of sodium or 2 500 lb. of potassium. The latter metal is, however, still mostly produced by distilling potassium carbonate and charcoal.

(2) *Calcium.*—Although of no economic importance as yet, calcium has for some time been produced by electrolysis of fused calcium chloride with graphite electrodes, at about the fusing temperature of the metal (800° C.). An interesting feature of this process is the method of collecting the metal, which tends either to dissolve in the electrolyte or, if the temperature is too low, to assume the useless spongy form. The cathode is placed above and just touching the electrolyte, and a button of the metal then forms on the tip of it; by gradually raising the electrode an irregular rod is produced. A kW-year gives about 450 to 500 lb. of calcium. The voltage efficiency is exceptionally low, and the energy efficiency only about 10 %.

Barium and Cerium may also be mentioned as similarly isolated.

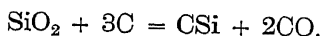
(3) *Magnesium.*—Metallic magnesium is produced by the electrolysis of fused magnesium chloride or, preferably and more often, fused carnallite, which contains both potassium and magnesium chlorides, with fluorspar (calcium fluoride) added to assist the globules of magnesium to coalesce. Chlorine is produced at the anode. An iron vessel is used as cathode, with graphite anode, the two being separated by a diaphragm in order to prevent the metal reaching

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the anode. The current efficiency is 75 % and the pressure 6 V per cell as against 3·2 V theoretical, giving an energy efficiency of 40 %. A kW-year produces from 1 100 to 1 400 lb. of magnesium.

C. Miscellaneous Furnace Products.

981. Abrasives; Silicon and Quartz Glass.—The accidental discovery and exploitation of carborundum, rivalling the diamond in hardness, and first produced by the Acheson process at Niagara Falls* at the end of the nineteenth century, has revolutionised the abrasive industry; especially is this so in the matter of grinding wheels, from the largest sizes down to dental wheels no larger than a threepenny bit. The raw material is silicon carbide, produced from quartz sand, together with carbon, in the form of anthracite or coke, combined by the intense heat of a resistance furnace, according to the chemical reaction



The actual charge is placed around a core of carbon in the form of granular coke, used as the initial heating resistance, and, in addition to the material required for the reaction, sawdust and salt are added in appreciable quantities; the gases given off from the former assist the CO to escape by making the mass porous, while the salt forms volatile chlorides of iron, aluminium and other metals accidentally present. Banks of several furnaces are used in rotation, as the operation of building up the initial charge and dismantling the final product take some time. Towards the end of a charge, as the resistance drops, very heavy currents, up to 20 000 amps. A.C., are used; the pressure dropping from over 200 down to 75 V. Each charge requires about 1½ days in the 2 000 to 3 000 kW size of furnace. The carborundum is obtained in the form of dark purple crystals for the most part, though the colour is due to impurities. The yield is about one ton per kW-year.

Chemically allied products of the electric furnace are siloxicon (used as a refractory lining for furnaces) and silundum, while from alumina (in place of silica) is obtained the abrasive alundum (artificial corundum or emery Al_2O_3) and also aloxite.

* One of the Authors (Mr. Meares) visited these works in January, 1896, and saw the furnaces in action. In the first of the many hydro-electric power-houses close by three large generating sets were erected and working. A few weeks later a photograph of the interior of this station appeared in an electrical paper, showing five sets in position; a triumph either of American engineers or—the photographer.

Quartz is also worked up in the furnace for the production of pure silicon, required in steel manufacture, as well as in various other industrial processes. In the Bottomley furnace a graphite resistor rod is buried in sand in a mould, and the current through it is gradually increased from 300 to 1 500 A at 30 to 40 V. Between 1 650° and 1 750° C. the sand becomes pasty next to the resistor and forms a gas-tight sheath round it, which is then blown out to the mould by the pressure of the carbon monoxide gas generated in the process. The surplus sand escapes through a grid. The process occupies from 1 to 1½ hr. and uses about 1 500 kWh per ton of fused silica produced. The use of quartz glass in the form of sheets, tubes, containers for mercury-vapour lamps, laboratory vessels and fine threads for suspensions is becoming increasingly important; it is made in the electric furnace as well as by the oxy-hydrogen jet. Other special glasses are similarly made in these furnaces. So also is fused crystalline magnesia, where 900 kW produce half a ton in 8 hrs., equivalent to 14 400 kWh per ton.

982. Graphite.—The process for the production of the allotropic form of carbon known as graphite was an accidental discovery in the carborundum furnace of Acheson, subsequently developed on a large scale by itself. The raw material is generally anthracite, but for special purposes the carbon residue of petroleum is used. The carbon is heated in an electric resistance furnace, similar to that employed for carborundum manufacture, along with the oxides of silicon, barium, iron, or aluminium. The latter appear to act in a catalytic capacity, though it is possible that an unstable carbide is formed and then broken up. The yield of graphite is about 5 500 to 5 700 lb. per kW-year. Carbon electrodes (§ 641, Vol. 2) can in a similar manner be graphitised, for purposes where they are more suitable in this form.

983. Distillation Products.—(1) *Phosphorus*.—Experimental work on a technical scale for the production of phosphorus, by distillation in an arc furnace, was carried out 33 years ago; and the bulk of the substance is at present so made.* There are several

* The original process of Albright and Wilson at Oldbury was kept rigidly secret. One of the authors (Mr. Meares) was in another section of the works, dealing with contractor's plant for electrolytic bleach, and only once managed to enter the furnace room in the dead of night. Strenuous endeavours were made by outsiders to obtain information and samples of the mixture used, culminating in the discovery of a foreigner, with a pair of binoculars, hiding in a slag heap!

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different processes, in which the raw materials calcium phosphate (bone ash) or phosphoric acid are reduced with carbon (generally charcoal) and, in the case of the former salt, silica also. The high temperature required, some 1 400° C., is supplied by an arc between very large carbon electrodes; and the vaporised phosphorus, protected from oxidation by a suitable gas, is distilled over and condensed in water or carbon monoxide. The yield by the Readman-Parker process is about 1 600 lb. per kW-year.

In connection with the production of phosphoric fertilisers, referred to in 973 *supra*, yellow phosphorus is made in the electric furnace and then oxidised to phosphoric acid before being combined with the other ingredients.

(2) *Carbon Bisulphide*.—This is made from sulphur and charcoal, by the Taylor process, and its use in the artificial silk industry makes it of industrial importance. The furnace has electrodes at the base, connected electrically by coke; the upper part is packed with charcoal; and sulphur is placed in an annular chamber surrounding the base. The sulphur is vaporised and combines with the heated charcoal as it rises; the carbon bisulphide vapour is then led out to condensers. The yield per kW-year is about 7½ tons.

(3) *Carbon Tetra-chloride*.—This is distilled and condensed in a manner very similar to that last described. The raw materials are common salt, coke, and quartz sand. The secondary product is water-glass (silicate of sodium).

ELECTROLYTIC PROCESSES NOT INVOLVING FURNACES.

984. Electrolysis of Brine.—Common salt (sodium chloride) and potassium chloride, dissolved in water, are the raw materials for a host of valuable electrolytic processes requiring much power, which it is impossible fully to describe here.* The chief products

* In the early experimental days much difficulty was experienced in designing heavy current dynamos that would stand up to the work. One of the authors (Mr. Meares) was in charge of such plant at Oldbury, the dynamos being double-wound parallel-coupled. These developed serious 'flats' from sparking at the commutator, which had constantly to be ground down. In the course of investigation a peculiar phenomenon was noticed. Of the two pairs of alternate + and - carbon brushes, one set could be lifted safely. If, however, these were dropped, and the other pair raised slightly, sparking began after a few seconds; this rapidly increased until, after about 30 secs., there was a roaring flash-over, which was instantly checked by dropping the remaining brushes. All the pundits of design in turn, after expressing

and bye-products obtained, according to the type of cell used, are—

- (1) Caustic soda (or potash), with chlorine gas and hydrogen as bye-products.
- (2) Hypochlorite of sodium (or potassium),

Chlorate	"	"
Perchlorate	"	"

The first results are obtained when the cathode and anode products of the electrolytic action are allowed to mix and react on one another; when the initial products are kept separate, the final product is one of class (2).

The chlorates and perchlorates are mainly used for the manufacture of explosives, while the hypochlorites are known as 'electrolytic bleach.' The caustic alkalis have innumerable uses in the chemical world and the chlorine gas is either liquefied or used for bleaching powder. The yields per kW year are of the following order:—

Hypochlorides and chlorates about $1\frac{1}{2}$ ton.

Caustic soda from 3 to 4 tons.

(1) *Caustic Alkali*.—As stated above, the primary substance obtained is always caustic alkali (Na or K) with chlorine, and in the alkali-chlorine cell these are not allowed to mix. Various types of cell are found. Those of Castner and of Kellner employ mercury cathodes, which form a dilute amalgam with the sodium (or potassium) as it is liberated. The anodes are of platinum or graphite; the pressure is about $4\frac{1}{2}$ V per cell; and the current efficiency is 90 to 95 %. Other types are the Jaice, Solvay, and Wilderman cells. There are also a number of so-called 'counter-current cells,' in which a treated asbestos diaphragm plays an important part; these comprise the Billiter-Siemens, Hargreaves-Bird, Townsend, Nelson, and other cells. An iron cathode is used, with graphite anodes. Finally there are counter-current cells with no diaphragm, such as the Aussig and Billiter bell-jar cells.

complete disbelief in the report sent in, came down and saw for themselves; but none could explain, and the machines went to the scrap heap. It was found, however, that very large circulating currents were present in the brush leads, and the time taken to work up to a crisis showed that an abnormal magnetic field was being built up in the process. The other author (Mr. Neale) had a similar experience in a plant using a 12-V dynamo rated at 2 000 A for electroplating. It was found impossible to operate with the two commutators in service, but the machine could be used to generate 1 000 to 1 200 A taken from one commutator.

A recent advance is the Vorce cell,* installed at Charleston, Va. It is 26 ins. diam. and 42 ins. high, with a cathode pot 22 ins. diam. and a steel container tank 38 ins. high. There are 24 Acheson graphite anodes 2 ins. square, which last about a year. Brine is fed to the cell from a tank under a head of 14 ins., controlled by a special glass device modified from that of Prichard. Caustic liquor discharges from the cathode pot through a device which breaks it up into small drops, and it is then conveyed to the evaporator. The chlorine is withdrawn through the dome, and, after cooling and drying, part is used for chlorine products and the remainder is liquefied. Hydrogen from the cell is used in chemical manufacture. The cells are arranged in 32 series of 70 cells each, operated at 1 000 A and 250 V for each series. The production is 0·859 lb. caustic and 0·793 lb. chlorine per kWh.

(2) (a) *Hypochlorates*.—In the hypochlorate cell there is no diaphragm or other device for keeping the chlorine and the alkali separate, and they combine as they are formed. In the Kellner cell, platinum-iridium bi-polar electrodes (§ 970) are used, and the brine circulates through the cell. In the Haas-Cettel cell carbon electrodes are employed.

(b) *Chlorates*.—In somewhat similar manner the chlorates can be obtained, either from an acid or an alkaline electrolyte of brine to which potassium chromate is added. Currents of the order of 1 000 to 1 500 A are used, with platinum-iridium anodes and graphite or iron cathodes. The pressure per cell is $4\frac{1}{2}$ to 5 V and a ton of chlorate of potash requires 7 300 kWh.

(c) *Perchlorates*.—Further electrolysis of an electrolyte, already converted to chlorate, with a high current density and low temperature, will give the corresponding perchlorate. Smooth platinum anodes and iron cathodes are used; the pressure is 6 V per cell; and about $1\frac{1}{4}$ kWh are required for a pound of the product.

985. Manufacture of Hydrogen and Oxygen; Ozone; Water Gas.—For the most part the industrial demand for hydrogen and oxygen is met by non-electrical processes, but the electrolysis of acid or alkaline water is nevertheless of considerable importance. It occurs incidentally as part of the process of manufacturing electrolytic caustic soda, where the gases are collected as a bye-product. In other cases, where cheap power is available, the process is under-

* *Et. Rev.*, Vol. 102, p. 754.

taken by itself.* The market for electrolytic hydrogen much exceeds that for oxygen, with the result that large quantities of the latter are wasted. The demand has been intensified for processes for hydrogenating oils in soap and allied trades (margarine, etc.). In these, absolute purity and uniformity are essential, and the non-electrical processes used for obtaining the gas for synthetic ammonia, etc., are unsuitable as they lack these properties. Palladium pumice, preheated—in an electrical furnace in the Siemens-Schukert process, but later by the outgoing gases—has been used for the purification of the gas. Pure water alone has practically no conducting power, so it is made conducting either by means of sulphuric acid, or sodium or potassium hydrate; these take part in the reaction but remain unaltered in solution. In the former case lead vessels and electrodes are used; in the latter, iron. Oxygen is liberated at the anode or positive pole and hydrogen at the cathode. Woven asbestos diaphragms between the electrodes are employed to keep the gases from mingling. In the Knowles cell the gases are washed by the fresh distilled water used for make-up in the cells; this removes the alkaline spray and returns it to the cells. The P.D. over each cell is from $2\frac{1}{2}$ to 3 V in alkaline cells and from 3 to 4 V in the acid type. The output of gases is proportional to the current, which produces them with 100 % efficiency, though the power efficiency is less as the working pressure is about double the theoretical (*viz.* 1.23 V) owing to the resistance of the electrolyte and the back E.M.F. of the cell regarded as a gas secondary battery. The yield of the two gases together is from 50 000 to 75 000 cu. ft. per kW year.

In the early Schoop electrolyser (acid type) the production is 1 000 cu. ft. of hydrogen and 500 cu. ft. of oxygen for 230 kWh; with the alkaline cells of Knowles, Garuti, Schukert, and Schmidt-Oerlikon the consumption of energy is from 125 to 140 kWh for the same quantities of the gases; that of the International Oxygen Co. gives even better results, the consumption being only 125 kWh for these quantities; this is due to the use of corrugated bi-polar electrodes (§ 970), the anode being nickel plated.†

* Useful data concerning the electrolytic manufacture of hydrogen and oxygen, together with notes on factors influencing the choice of process are to be found in 'The Application of Oxygen and Hydrogen to Industrial Operations,' by F. P. Wilson, Jr., *Gen. El. Rev.*, Vol. 31, p. 197.

† Further information will be found in the *Jour. I.E.E.*, Vol. 66, p. 548.

In the manufacture of electrolytic alkali (§ 984) chlorine and hydrogen are given off at the anode and cathode respectively and are similarly collected separately. A further industrial process in which hydrogen is obtained electrically is by the decomposition of acetylene into carbon and hydrogen.

Peroxide of Hydrogen may also be mentioned here as an allied product, also produced electrolytically.

Ozone.—The demand for ozone for medical, bacteriological, and sanitary purposes has caused a number of processes to be devised for its production from dry oxygen, or simply from air, by passing it through an ozonizer in which a silent high-tension discharge is maintained. Pressures up to 100 000 V and ordinary frequencies up to 100 cycles are used. The efficiency of all the processes is very low, namely, from 4 to 12 %, and from 40 to 150 gms. are produced per kWh. The Ozonair system may be mentioned as one of the least inefficient.

Water Gas.—The ordinary method of preparing water gas (a mixture of carbon monoxide and hydrogen) is by passing steam through incandescent carbon—generally coke. This may be maintained at working temperature by using it as a resistor in an electric furnace. In some plants wet peat is fed on to the surface of the heated coke bed, thus dispensing with the necessity of an independent steam supply. The gases and moisture from the peat are then dissociated by the incandescent coke to water gas, while the carbon residue of the peat in its turn becomes incandescent.

986. Other Technical Chemicals.—These need not detain us long, as the production is not on a scale requiring much power.

(1) *Permanganate of Potash*.—Electrolytic oxidation of potassium manganate has now taken the place of older methods in preparing the permanganate. Caustic potash is added to the electrolyte, which requires about 3 V for decomposition, using iron anodes and cathodes. The current efficiency is low, under 70 %, and about 3 lb. per kWh is the yield. The sodium salt (Condy's fluid) is obtained similarly from the manganate.

(2) *Anthraquinone*.—This substance, used in the preparation of alizarine for dyeing, is produced electrolytically in conjunction with anthracene and chromic acid, with a high current efficiency and a pressure of 3 V per cell. Lead electrodes, separated by a diaphragm, are used.

(3) *Persulphates*.—Ammonium and potassium persulphates are

prepared by the electrolytic oxidation of the corresponding sulphates, with a platinum anode and lead cathode. A current efficiency of 70 % is obtained, with a pressure of 7 V per cell. The yield is about 1 lb. per kWh for ammonium and less for potassium.

(4) *Perborate of Sodium*.—This, which is used in bleaching, is prepared by electrolysis of a mixture of borax and sodium carbonate with a trace of chromate of soda, the pressure being 6 V per cell. Platinum gauze anodes and tin or aluminium cathodes are used.

(5) *Iodoform*.—To produce iodoform an electrolyte of sodium iodide, sodium carbonate, and alcohol is electrolysed between a platinum anode and a lead cathode, separated by a diaphragm. The pressure required is from 2 to $2\frac{1}{2}$ V per cell, and the current efficiency about 90 %. Bromoform is similarly prepared.

(6) *Miscellaneous*.—Bare mention must suffice of various nitrites, of sulphuric acid, hydroxylamine, cyanides, cuprous oxide, hydrazine, hydrazoic acid, and chromous salts—all of which have been the subjects of research and some of technical success by means of electrolysis.

987. Extraction and Refining of Copper.—(1) *Extraction*.—Although the use of electrolytic copper for electrical work is universal, the refining of the raw metal long preceded its electrical extraction from the ore; indeed at the present day purely metallurgical methods account for most of the commercial copper produced. Many processes for wet electrolytic extraction have been devised in the laboratory, but very few have proved commercially practicable. Impurities in, and irregular composition of, the ore, and therefore also of the electrolyte, are the chief causes of the technical difficulties met with. In the processes still alive, the ore is first roasted and lixiviated with sulphuric acid; and the solution is then electrolysed, using anodes of lead or magnetite and cathodes of copper, with a diaphragm protecting the anode. A pressure of about $2\frac{1}{2}$ V per cell is required; current density 12 to 20 A per sq. in.; and a yield of 1 ton is obtained for 2 200 kWh. The acid remaining in the bath is used over again.

(2) *Refining*.—The purest copper obtainable by the earlier metallurgical methods of refining contained from 1 to 2 % of impurities, including appreciable quantities of the precious metals. Not only were these lost, but the conductivity is seriously diminished by any admixture; with the result that the present-day electrolytic

copper has a higher conductivity by about 3 % than Dr. Matthiessen's standard of what was believed to be pure copper about the year 1864. As already mentioned above, processes have been tried for obtaining pure copper electrolytically direct from the ore; but all copper now used for electrical purposes is obtained by the electrodeposition of commercial copper on to a cathode consisting of a sheet or tube of previously refined copper. Ordinary commercial copper rods are used as the anode, in a solution of sulphate of copper (12 to 20 %), with 4 % or more of free sulphuric acid added and a small amount of hydrochloric acid. The current density varies between the very wide limits of 4 to over 40 A. per sq. ft. of the cathode surface. With high densities the yield is greater but the deposited metal is less adherent and may even be spongy. The pressure employed is from 0.2 to 0.3 V per cell. The 'impurities' fall to the bottom of the cell as anode mud, from which the precious metals are subsequently extracted; the value of these is one of the chief economic factors in the process. The final product is practically pure, *viz.* 99.95 %. To produce a ton of electrolytic copper requires the expenditure of from 150 kWh to 300 kWh—according to the system used. At the other end of the scale the process is utilised (as a cheap substitute for silver) in the calibration of current measuring instruments and as a coulometer.

Elderly readers of the *Electrical Review* will recollect the long series of articles in that paper on the subject of the 'Elmore patents,' about the year 1891, the criticism being directed on the financial rather than on the technical merits of the processes. In these a revolving tubular mandrel is used as cathode, and on this electrolytic copper is deposited by the method described above, and burnished simultaneously. Later improvements of the process are in use at the present day, and in France a similar method has been used for the electrolytic production of iron tubes also.

988. Extraction and Refining of Gold.—(1) *Extraction.*—Although purely metallurgical means are for the most part employed in the extraction of gold from its ores, the electro-chlorination process of Greenawalt has been used to some extent. A liquid, electrolytically produced from a solution of salt and sodium bromide, and therefore containing free active chlorine and bromine, is run through the roasted and crushed ore. The solution thus obtained is electrolysed between lead electrodes, arranged in a long

series, so that the liquid has to travel slowly through a long and tortuous path. In this way the gold (with any silver present) is collected at the cathodes in the form of a fine black colloidal powder. After recovering the silver, the gold goes to the crucible.

Electricity is also used, as an alternative to the ordinary zinc recovery process, in the treatment of the residues and slimes of the 'cyanide process,' which is used in connection with, and following, the amalgamation process of treating low grade ores. The electrolyte is a very weak solution of cyanide of gold. Here again, in the Siemens-Halske process, the electrolyte is made to travel over a very long path between multiple sets of paralleled iron anodes and lead cathodes, each wrapped up in bags. Prussian blue forms on the anode and the gold deposits on the lead cathode and is subsequently recovered in the crucible. The pressure required is from 4 to 5 V and the current efficiency is very low.

(2) *Refining*.—Before refining, gold bullion is associated with varying proportions of silver, copper, platinum, palladium and lead, the gold generally accounting for about 94 %. It is cast into thin slabs, which become the anodes, while pure gold foil constitutes the cathodes; both are multiple and parallel (Fig. 413). The electrolyte is chloride of gold with free hydrochloric acid added. The reactions are very variable, depending upon temperature, current density and other factors such as polarisation at the cathode. Of the other metals present, the silver is precipitated as chloride and the lead as sulphate, by the addition of sulphuric acid. Copper, platinum, and palladium accumulate in the electrolyte, while chloride of gold has to be added to it from time to time.

989. Extraction and Refining of Silver.—(1) *Extraction*.—As in the case of copper (§ 987), the electrolyte extraction of silver from its ores offers many technical difficulties, and has made even less progress. A commercially successful process has a large field open to it, for there are large areas containing silver ores (generally sulphides, which are the most difficult to reduce)* in the neighbourhood of easily developed water power, in many parts of the world.

* Flotation concentration in various forms is employed in the treatment of these ores, electricity being used for the work. The minerals-separation machine has a capacity of $1\frac{1}{2}$ tons per sq. ft. of area per day, including the agitation compartments, and consumes some $4\frac{1}{2}$ kWh per ton of ore. Carpenter, *Proc. Inst. C.E.*, Vol. 224, p. 298.

At the Burma Mines the Mansan falls are developed and used for power, but not, so far as the Authors know, for the electrolytic extraction of the silver, lead, zinc, and copper produced. The silver mines in what is known in the vernacular as the 'rupee land' of Kulu, in northern India, overlook a perennial hill-stream of large volume; but they have long been abandoned because the cost of transporting the ore from this remote valley to where it could be smelted exceeded the value of the metal recovered.*

(2) *Refining*.—Silver refining by electricity is commonly practised. The methods employed vary according to the constitution of the raw material; whether the crude silver from the better class ores; the silver residue from lead ore; the slimes from copper refining; bullion; or old silver-plated articles. The anodes (of this very variable composition) are cast and placed in cells with nitric acid and nitrates and electrolysed. The greater part of the mixed bag dissolves, the balance going into the slimes, where most of the precious metals congregate. The cathodes, on which the silver is deposited, are of fine silver foil. A pressure of $1\frac{1}{2}$ V per cell is required, and a current efficiency of about 95 % is obtained; the yield of practically pure silver being one ton to 420 kWh in the Moebius process and somewhat less in the Balbach-Thum process. There is generally some gold present in the anodes, sometimes also platinum, tellurium and other rare metals; copper, tin, antimony, bismuth, zinc, iron and cadmium have also to be coped with. Consequently the slimes and the electrolyte require further treatment for the extraction of such of these metals as are worth the expense. Bismuth, antimony and cadmium are all refined electrolytically, as well as metallurgically.

990. Extraction and Refining of Nickel.—The manufacture of ferro-nickel, for use in nickel-steels, has already been referred to in § 979. In addition there are a number of 'wet' processes of electro-deposition, either (a) from a solution of the chlorides of nickel, calcium, and copper, or, (b) from the sulphate of nickel. Among the former are the Thum, Orford, Browne and Hoepfner, with a yield of 1 ton for 2 500 to 4 000 kWh; the Hybinette process comes in the second category. All are complicated by the varying composition of the raw material, which contains many other

* The 'oldest inhabitant,' who took Mr. Meares over the workings, assured him that bears and bats were the only creatures inside; but the ore seemed too good to lie there.

elements. Platinum and palladium are recovered from the slimes, and are of economic importance to the process. Copper, iron and cobalt are also generally present and cause much difficulty; the copper is more often electrolytically separated in a preliminary operation, using copper cathodes and carbon anodes, while the iron and remaining traces of copper are removed chemically; subsequently the nickel is deposited on pure nickel cathodes, using graphite anodes.

991. Zinc Extraction.—As in the case of nickel, electrolytic processes are in use for the extraction of zinc both from chloride and sulphate solutions of the ores, requiring respectively 3 000 and 5 000 kWh per ton of yield; but non-electrical methods are still the main source of spelter. The purification of the metal is carried out by distillation, with which no other can compete. Electrical 'wet galvanising' is to some extent replacing the older method of the molten bath; *vide* § 994 (g). Although the metal is so extensively used, there is vastly more raw material readily available than can be economically utilised, in the form of tailings from the complex lead-zinc-silver-bismuth-antimony ores of Australia and Burma;* and sooner or later these will certainly come into their own. Aluminium is sometimes used as a cathode in the process.

992. Lead Refining.—There are electrolytic processes for the extraction of lead from its ore, but they do not compete economically with the ordinary smelting methods. Electrolysis is, however, used in competition with older methods in refining the metal and recovering the silver residue, the bismuth and the antimony with which it is generally associated. The Betts process is the best known and employs an electrolyte of lead fluosilicate with excess of the corresponding hydro-fluoric acid. Electrically deposited lead anodes and cathodes are used; the pressure rises from 0.25 to 0.4 V

* The tailings of the Burma Mines constitute a romance in metallurgy. These mines were worked by the Chinese for centuries in the dim past, and abandoned when the inroad of water could no longer be coped with by the primitive bamboo pumps then made. Only the first runnings of the lead, which carry most of the silver (a fact made use of in the Pattinson and other modern processes) were obtained by charcoal smelting; and vast heaps of rich lead-zinc tailings accumulated. When the mines were accidentally rediscovered not long ago they were properly developed on modern lines, including hydroelectric power. The old Chinese tailings were worked through again for lead and the balance of the silver, along with some of the minor products, but the zinc remains in the new tailings for future extraction—probably by electrolysis—when the market for spelter becomes more favourable.

as the anodes dissolve, and a yield of 1 ton (practically 100 % pure) requires only 100 kWh, the current efficiency being 90 %. The slimes retain all the above foreign matters, except zinc and iron, and they are separately recovered.

Electrolytic methods of preparing white lead are also used; as also various other pigments, *e.g.* chrome yellow.

993. Tin Recovery.—The extraction and refining of tin by the old metallurgical methods meets with no competition; but the recovery of the metal from tin-plate (*i.e.* tinned steel) in the form of old tins and scrap is carried out electrolytically. The scrap has first to be cleaned and freed from grease and solder. There are processes employing hydrochloric or sulphuric acid, ferric chloride and tannic chloride as solvents. The Goldschmidt process uses the scrap as the anode, in a solution of caustic soda, and deposits the tin on an iron cathode. The pressure per cell is $1\frac{1}{2}$ to 2 V. The last traces of the tin, where it is alloyed to the steel, remain behind.

994. Electroplating and Electrotyping.—(1) *Plating.*—The metals ordinarily used for electroplating are gold, silver, nickel, chromium, copper, brass, zinc and lead; but iron, platinum, cobalt, tin and bronze, are also used to a limited extent. The thickness of metal deposited, t , in inches per hour, may be found approximately by the empiric formula $t = I / 144 wx$, where I is the current density in amperes per sq. ft., w = weight of the metal in lb. per cu. in., and x = Ah required per lb. deposited. In all cases the article to be plated is first thoroughly polished, and cleansed by caustic soda and/or acid pickling; and both these processes may be aided by the use of electricity. In electric scouring the work is made the cathode in an alkaline solution; the hydrogen evolved removes oxide scale and dirt, while the alkali removes any grease. In electric pickling the work is similarly made the cathode in an alkaline solution, but the direction of the current is reversed periodically. Subsequently the cleaned and polished article is made the cathode in the plating bath, with an anode of the pure metal to be deposited.

(a) *Gold.*—Electrolyte, the double cyanide of potassium and gold, with potassium cyanide in excess. Pressure, 4 V per cell.

(b) *Silver.*—Electrolyte, potassium-silver cyanide, with added potassium cyanide; 1 V per cell; 3-6 A/sq. ft. [The International ampere is determined by the rate of deposition of silver (Vol. I, § 3); the same apparatus being used as a standard coulometer.]

(c) *Nickel*.—Electrolyte, nickel sulphate with ammonium sulphate and a trace of baric or citric acid. Pressure per cell, 3 V; current density, 3-6 A/sq. ft.

(d) *Copper*.—"Acid" bath: copper sulphate and sulphuric acid; 25-30 A/sq. ft. (higher with agitation). Inapplicable, without preliminary cyanide coating, to any metal attacked by H_2SO_4 or reacting with CuSO_4 . "Cyanide" (or "alkaline") bath: double cyanide of copper and potassium (or sodium) with excess of alkaline cyanide; work at about 120° F.; pressure 2 to 4 V. *See also* Coulometer, § 987.

(e) *Brass*.—That an alloy of two very dissimilar metals should be capable of ionic transfer through a solution is strange, as the copper alone would appear likely to deposit. But in an electrolyte consisting of a mixture of the double cyanides of (i) potassium and copper, and (ii) of potassium and zinc, with the usual excess of potassium cyanide, brass of ordinary composition can be plated from the anode without change of proportions. Pressure, 4 to 6 V per cell. *Bronze* is similarly plated.

(f) *Copper and Nickel*.—Experimental work has for some time been in progress for the simultaneous deposition of copper and nickel in a form similar to the alloy known as monel metal.

(g) *Zinc*.—"Wet galvanising" is carried out with an electrolyte of zinc sulphate, together with sodium (or magnesium) sulphate, the pressure required being $3\frac{1}{2}$ V. It has been stated by Carpenter* that three plants, *viz.* the Anaconda at Great Falls, the Consolidated Mining Co. at Trail and one at Hobart, supply practically all the electrolytic zinc of the world, some 650 tons a day. They all use sulphuric acid leaching followed by electrolysis of the zinc sulphate solution, with a C.D. of about 30 A per sq. ft. of cathode. Great purity of the electrolyte is essential; lack of it caused early failures.

(h) *Lead*.—For plating lead an acid solution of lead borate or fluosilicate is used as electrolyte, and worked at 10-20 A/sq. ft. This is one of the latest developments of plating, and finds its field in coating other metals so as to render them safe from acid corrosion—for example, in copper battery connections, where the least trace of copper in the cell has disastrous results.

(i) *Chromium*.—This metal is very hard—more so than hardened steel—[979 (5)], takes a good polish, and is very resistant to tarnish and chemical action. Chromium plating is used

* *Proc. Inst. C.E.*, Vol. 224, p. 806.

extensively for motor-car parts, taps, etc.; and the process is used for making plates and dies for printing currency notes and the like, where very many copies are required, and for gauges, which last up to twenty times as long as steel gauges. The metal is often plated in combination with underlying coats of copper and/or nickel. The solution used as electrolyte consists of $\pm 25\%$ chromic acid with 0.3% chromium sulphate * (or carbonate), and a high current density of 150 to 200 A per sq. ft. is used. Lead anodes are used, and the chromic acid is replenished as necessary. The bath has to be kept cool artificially, and the current efficiency is only about 30% .

(2) *Electrotyping*.—The reproduction of facsimiles in metal from a negative cast (of plaster of Paris, gutta-percha or wax) has many applications beyond the printing press, where it is used for reproducing steel or copper engraved plates, wood blocks, half-tone blocks and set up type as an alternative to stereotyping. The cast is made to conduct by a coating of graphite; and an anode of electrolytic copper then deposits the metal on this in an electrolyte of copper sulphate with added sulphuric acid. A pressure of 1 V is sufficient. When iron electrotypes are required, the electrolyte is ferric chloride with ammonium (or calcium) chloride added. Analogous methods are used for building up metal to repair wear or breakage, as an alternative to the older method of the oxy-acetylene blowpipe or the competing electrical method of arc welding with metal electrodes (§ 652). It is sometimes practicable to build up worn parts *in situ* by building an electrolytic bath round the part concerned, filling the vat with appropriate solution, and arranging one or more anodes to carry current into the solution and replace the metal deposited therefrom on to the cathode (the worn parts). Where this method is used, an insulating varnish or similar means may be employed to prevent deposition of metal on parts which are necessarily within the vat but which do not require building up. The working conditions must be adjusted in each case to ensure a firmly adhesive deposit of satisfactory structure. Among the other electrotyping processes used are metallising wood, putting driving bands on shells and bullets and making records for gramophones in the intermediate stage between the original wax and the final sale product.

* *El. Rev.*, Vol. 101, p. 125, and Vol. 102, p. 53.

995. Electrolytic Synthesis.—Although mainly in the experimental stage at present, the ever-expanding field of synthetic chemistry offers a promising outlook for the electrolytic technologist; and already various organic compounds are so made. Successful operation of the principle generally involves cases where one of the constituents can be obtained electrolytically in the nascent state and can be brought, in that very active state, into contact with the other constituents. White lead can be so made, by electrolysing lead anodes in a solution of potassium chromate and carbonate, CO_2 being blown in to replace that combining with the lead.

996. Electrical Precipitation.—Every engineer and nearly every housewife has observed the streak of dust which is collected and deposited on walls or ceilings traversed by a cleated or otherwise exposed electric circuit, due to the electrostatic effect of even low-voltage lines. The property is made use of industrially for the electrical precipitation and collection of dust of all kinds. Mechanical rectifiers of the commutator type, driven synchronously by A.C., are generally used for this work (§ 416). The two chief patterns of precipitator have plate and tube collectors respectively; the former uses wire or comb electrodes between earthed plates, while the latter uses wire along the axis of the earthed pipe.* Plates about 12 ins. apart are used, with a pressure of the order of 40 kV; higher pressures, up to 80 kV, have been tried, but with no great gain, and all manner of electrodes and frequencies appear to give much the same results. The charged electrode is generally the negative, while the positive of the L.T. supply is connected to the earthed electrode. The velocity of flow of the air or gas to be treated is from 400 to 450 ft. per minute. If the precipitate is non-conducting and very finely divided, it may be necessary to inject moisture or other conducting ingredient into it; otherwise there is a tendency for the discharge to reverse its direction, with

* A paper, 'Electrical Precipitation,' by A. Grounds and H. W. C. Henderson (*Proc. South Wales Inst. of Engineers*; see also *El. Rev.*, Vol. 102, p. 706) describes the Lodge-Cottrell precipitator with either plate or pipe treater. The electrical equipment includes a step-up transformer, a mechanical rectifier (§ 416, Vol. 2) in the form of a rotating switch driven by a $1\frac{1}{2}$ H.P. synchronous motor; control and regulating gear; and automatic safety devices. A certain installation, treating 6 million cu. ft. of gas per hour uses 12 plate-type chambers and 6 motor-generator

consequently increased power consumption.. Any fumes can be precipitated—including domestic smoke, if it were commercially feasible. Zinc oxide is a case in point, when it is condensed after volatilisation in the smelting of the complex silver ores. Producer gas, and the gas from blast furnaces, can in this way be cleaned before use in gas engines, sometimes with a sensible return from the value of the dust removed and always with a great saving in wear and tear of cylinders and pistons. Where pulverised fuel is used, the flue gases may be cleaned by precipitation ; * and every sort of dust found in the air of workshops, or in the ventilating air supplied to them, may be purified. Apart from the mere removal of the solids, the ozone and oxides of nitrogen produced have a sterilising effect on the air treated. The air or gas is not cooled in this process, as it is in, for example, the wet 'scrubbing' of town and producer gas ; and the removed dust (unless deliberately humidified, as mentioned above) is also dry. Solid matter and condensable vapours can be precipitated and collected separately, the dust being first extracted at a temperature high enough to prevent the vapour condensing, and the vapour being subsequently collected in a 'mist' precipitator after the gases have cooled sufficiently. From time to time the supply is cut off, and the electrodes are rapped with a hammer to remove adherent deposits. The dust recovered has, in some cases, an intrinsic value high enough to offset the cost of the treatment, and from 85 to practically 100 % of that present is removed. As an instance, the dust removed from cement kilns often contains much valuable potash. It should be added that every precaution must be taken for ensuring the safety of operatives where these extreme high pressures are used, such as the *automatic* cutting off of the supply when entrance to the apparatus chamber is made.

Table 216 is abstracted from a paper by P. E. Landholt of the United States Research Corporation.

Experimental work has been carried out on fog and cloud dispersion, by dropping fine and highly electrified sand from aeroplanes, thus causing coalescence of the particles which act as nuclei ; and, however little effect this may have on the British climate, the principle has possibilities in other directions.

* See 'Flue Dust Recovery,' by H. W. C. Henderson: *World Power*, May and June, 1928.

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In some ores the ferrous material is non-magnetic in the raw and only becomes weakly magnetic after roasting or calcining.

Magnetic separators are also used to get particles of iron out of the 'slip' in ceramic manufacture (*see also post*, 'electro-osmosis'), into which they have made entry during grinding or other processes. Similar applications are met with in the purification of grain,* sugar, and various chemicals, as well as in the sorting out of scrap metal sweepings, etc.

Slag reduction and the reclaiming of unburnt coal from the ash-pit by these means is already of high industrial importance; true clinker generally contains enough magnetic material to enable separation to be effective. In this work from 0.6 up to 2.4 kWh are required per ton of ashes treated.

There are many types of separator, each designed for its own special conditions, but the principle is the same throughout. The solid, granular, or liquid material to be treated is passed along a belt or other conveyer, so that it is spread out evenly before passing under the pole pieces of the magnet—or, more often, of the successive magnets, so that what escapes the first may be caught by the next. The intensity of the magnetisation varies according to the nature of the magnetic material, and is sometimes very intense. The iron particles may either be caught up on the poles and released at intervals by demagnetisation and flushing; or they may be intercepted by another conveyer and thus removed in process of being caught; or, again, they may be picked up by revolving magnets at one point and, when these are demagnetised automatically further on, dropped into a slot or receptacle. For the most part multiple D.C. magnets with salient poles are employed; but both single-phase and two-phase A.C. magnets have also been used† and repulsive as well as attractive forces are brought into requisition. The power involved is comparatively small, of the order of 1 to 5 H.P., including both the driving of the machine and the energising of the magnets. (*See also* § 809.)

(2) *Electrostatic Separation*.—Some of the applications of elec-

* A suggestive application is that in which the seed of the parasitic dodder is eliminated from that of clover. This is rendered possible owing to the fact that these seeds become sticky when moistened, so that iron filings added to the bulk adhere to them alone, and enable them to be removed in a magnetic separator. (*Compressed Air Magazine*, Vol. 29, p. 896).

† *El. Rev.*, Vol. 98, p. 114.

trostatic separation have already been mentioned in the preceding paragraph on Electrical Precipitation.

(3) *Electro-Osmotic Separation*.—It has been found that if a current is passed through a porous diaphragm, immersed in an electrolyte, there follows a flow of the liquid through the diaphragm (electrical endosmose), generally from anode to cathode, but sometimes in the opposite direction; and if there are suspended particles in the liquid, then as the liquid travels towards the cathode there is also a migration of the solid particles towards the anode (kataphoresis).^{*} These properties are used industrially in various ways. In the purification of very finely divided clay suspended in water (slip)—see also 'electromagnetic separation' *ante*—D.C. at 60 to 100 V is applied; it drives the particles of clay towards the anode (usually a slowly revolving gauze metal drum) and any metallic oxides present—not necessarily magnetic, as in the other method—towards the cathode. The degree of purification depends largely on the applied voltage.

The *electro-osmotic purification of water* for laboratory purposes, certain manufacturing processes (including brewing), and for boiler feed make-up depends on the passage of D.C. through a three-compartment cell. The anode and cathode are in the outside compartments and 'raw' water is fed to the centre compartment, which is formed by porous diaphragms. Under the influence of the current flow, acidic impurities collect in the anode chamber and alkalies in the cathode chamber. By passing water through the central compartment of one cell to that of another in a cascade arrangement, a high degree of purity is ultimately attained. It is claimed that a purifier of this type, delivering about 3 tons of water per 8-hr. day consumes about 20 kWh per ton. A number of cells can be used in series at each step of the cascade to suit the supply voltage. The voltage required per cell increases as the purification proceeds.

Electro-osmosis is also employed in tanning and in the segregation of emulsions and other colloidal suspensions, such as cod-liver oil, linseed and cotton-seed oil, sugar, etc. Its use for the partial removal of water from peat has been the subject of several patents. The injection of narcotics and drugs through living tissue by this

^{*} British Association: Second Report on Colloidal Chemistry, 1919. (H.M. Stationery Office.)

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means is also familiar to modern medical men and dental surgeons, and involves electrolysis also.

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(See also, if required, further references to technical papers in the Dict. of Applied Physics, Vol. 3, p. 316.)

CHAPTER 39.

SPECIFICATIONS: DEPRECIATION AND MAINTENANCE.

SPECIFICATIONS AND ALLIED MATTERS.

999. Specifications Generally.—When any engineering works are to be carried out, the exact relative positions of the purchaser and the contractor must be clearly laid down, so that if disputes occur the arbitrator or the Court has material for a decision; and also the precise scope of the works must be clear. The first of these matters is dealt with by the Conditions of Contract; the second by the Specification. Generally the 'Form of Model General Conditions recommended for use in connection with Contracts for Electrical Works' (§ 1054), issued by the *I.E.E.*, will be found applicable, or at least a useful guide.* It first saw the light in 1902-03 and has often been revised since. The document consists of: Form of Tender; Form of Agreement; Form of Guarantee; General Conditions relating to the Works and the manner of carrying them out. For the technical side of the work a specification and drawings and (in the case of work to be paid for by measurement, or involving an unascertained number of any components) a schedule of prices is required.

The Consulting Engineer's work is very exacting and requires great skill and experience; where these are absent the result may be deplorable. It is notorious that in the case of works in the Dominions and India the drawing up of the specification, and the preliminary work of investigation, is often left to the firm of engineers who have originated, and are predestined to carry out, the work. The engineer nominally responsible takes the credit and the firm gets the dollars, as an American expressed it to the writer. So long as the firm employed go into the matter with their eyes open, and are told that others will be invited to tender, this is unobjectionable; but they should be paid for their work as

* The Association of Consulting Engineers also has two useful forms of 'Conditions of Contract' for civil and for mechanical and electrical contracts.

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consultants, even though the dual rôle of consultant and contractor would not be tolerated in older countries. It may be mentioned that consulting engineers, like medical practitioners, are prohibited from anything in the nature of advertisement, although there is no General Council behind them to enforce the rule; but they are subject to stringent rules as to 'Professional Conduct,' issued by the leading institutions, and very few cases of breach arise.

In succeeding paragraphs brief notes are set down relating to the data required to be given or received in regard to plant of various types. A full specification for wiring work has already been given in Chapter 23, as this work is a necessary concomitant of nearly all contracts; but to print even skeleton specifications of plant and mains, etc., would take up too much space, while perhaps serving no useful purpose.*

Owing to standardisation (§§ 1055 to 1057) there is seldom any necessity to specify the details of construction of individual parts in ordinary stock apparatus; and a great deal of the matter in an average purchaser's specification might in most cases be omitted, thereby reducing the perhaps unavoidable prolixity of all such semi-legal documents. As a cynical writer has expressed it:—

Why specify that an armature should be made of Swedish charcoal-iron plates and be wound with copper wire of 100 % conductivity? If the manufacturer can give us the output, efficiency, and temperature rise specified with a solid brass armature wound with iron wire, why not let him?

The true object of the specification is to state in unmistakable terms exactly what the purchaser requires in the way of *results* and what he is *not* prepared to accept in the way of apparatus. If he is prepared to accept any one of several alternatives he should leave the matter to the tenderers. In one case known to the Authors a maximum speed for Diesel engines was specified which ruled out several well-known makers; the purchaser could not benefit by such action. Each tenderer will inevitably tender for the standard construction of his firm, unless the apparatus is altogether special, and it is to the advantage of both sides that he should do so. It is not unusual for a contractor to enclose with his tender his own set of conditions, different from, and conflicting with, those sent out with the specification; unless the latter is clearly at fault such tenders deserve to be rejected. In all ordinary cases, if the data enumerated in the following paragraphs are given

* Details of most of the separate items in §§ 1000-1011 will be found in the Index.

or asked for, as the case may be, little else will be necessary; and special cases should be dealt with by specialists. Where the purchaser knows what results he wants, but cannot draw up a proper specification, it is far better (in the absence of a consultant) that he should set forth the *desiderata* and invite tenderers to make their own suggestions, rather than to go to one firm only and be tied hand and foot to that firm; the latter course is, however, only too common.

It is not unusual for a specification to ask for information as to similar plant constructed by the tenderer, which can be inspected by the purchaser; for there is always some risk in giving an order to a firm which has hitherto not manufactured in so large a size, or in accepting experimental types that have not been fully tried out.

As regards the vexed question of the 'lowest tender,' it is a safe assumption that the average of all tenders more nearly represents the actual selling value of the goods than either of the extremes; a tender which is much below all others should be scrutinised with the greatest care.* The purchaser nearly always states that he does not bind himself to accept the lowest or any tender; but where some public body, such as a municipality, is the purchaser, it invariably causes trouble if the lowest tender is rejected by the engineer. Looking at the matter from the manufacturer's point of view, a lot depends on the state of the order book at the time; in recent years many orders have been taken with no margin of profit at all, merely in order to keep the skilled staff going until better times.

Useful notes on the calculation of running costs (including capital charges, depreciation, repayment, etc., as well as energy, maintenance, repairs and labour), in relation to the consideration of tenders, are given by J. C. Connan, *El. Rev.*, Vol. 93, p. 564.

1000. Further Notes on Specifications and Conditions of Contract.—In an interesting paper by F. S. Sells (*Journ. I.E.E.*,

* An amusing instance came to the notice of one of the Authors some years ago in Oregon. Tenders were invited for a huge quantity of earth for the reclamation of a strip of foreshore, and one tender was so far below the rest as to suggest an error of calculation. It was accepted in haste; and the tenderer thereupon completed his purchase of a hill too steep to build upon, in the centre of the town, and not far from the proposed reclamation. This hill he scoured away by means of high-pressure water jets, washing the debris down timber flumes to the reclamation, *and getting paid for removing it*; with the result that he obtained several acres of very valuable building land in place of a useless hill-top.

Vol. 49, p. 199), the author gives two definitions of a specification :—

Halsbury's *Laws of England* says : 'A specification is a detailed description of building, engineering, or other works executed, or proposed to be executed.'

Ball, on *Law Affecting Engineers*, says : 'A written description and plans, more or less complete, defining methods of construction, etc., to be used, prepared by the engineer for the approval of the employer and for the guidance of the contractor.'

The first of the definitions says a specification is a 'detailed' description, the other admits that it is 'more or less' complete, and rather a guide than definite instructions. If there is already such a vital difference in the interpretation of the word 'specification,' can we wonder that the opinions as to how a specification should be drawn up in practice are equally conflicting?

A specification must be clear; it must leave no room for doubt as to what is in the mind of the man who issues it, for, unless this is the case, it cannot possibly be clear to the man who is expected to work to it. In many cases the want of clearness in specifications is the first bone of contention. Clearness, however, does not necessitate elaboration of detail. The author holds it to be advantageous to both sides if only such details are inserted as refer to the requirements of the purchaser. Details of construction should, as far as possible, be avoided; they should form part of the tender.

While specifying, as precisely as possible, what is required, it is generally both unnecessary and inadvisable to name a particular manufacturer; there are, however, many exceptions to this wholesome rule, as in cases where a specialised article, made by a particular firm, has been found by experience superior to cognate articles obtainable in the open market under the local conditions obtaining. Even where an article is specifically named, tenderers should generally be permitted to offer alternatives for consideration, as otherwise progress is impossible.

The exact scope of the contract should always be laid down. Confusion is often caused by failure to state precisely what in the way of builder's work, foundations (*e.g.* grouting in), etc., is or is not to be done by the purchaser or the contractor respectively. Similarly, as between two tenderers whose work overlaps, the exact boundary to which each is to work must be laid down; for instance, the common bedplate or the coupling for a combined generating set or a motor pump or the like, where the electrical and mechanical components are supplied by different firms, may be cited; or, to take another example, the taper and special pipes between a water turbine and its main pipe-line. Again, questions of import duty, freight, and carriage to site should not be left to chance and an arbitrator.

Perhaps there is no duty which an engineer is called upon to undertake which is a more responsible one and requires greater care than the framing of a contract. The importance of the choice of the correct words and their proper collocation cannot be exaggerated, for when a dispute arises between the parties to a contract all that a court of law can do is to interpret the language contained in the document which purports to set out the matters on which the parties actually came to an agreement. A moment's reflection will show the serious inconveniences which would arise if the practice were otherwise, and if the parties to an express contract were allowed to argue that language deliberately employed in the written document did not actually set out their intentions. It is well, therefore, for an engineer, before he signs a contract, to analyse closely the expressions which are employed therein, so that he may make certain that the phraseology is so clear and the terms so explicit and every contingency provided for that, if submitted to a court of law, the language employed will support the interpretation which he desires shall be put upon it. Disputes often arise from the fact that the parties to a contract are mistaken in their ideas of their obligations thereunder; it is always a wise precaution in all important dealings to seek legal advice, and in none more so than in the preliminary stages of a large contract, so as to ensure, as far as it is possible to do so, that the real intentions in relation to the contract appear in clear and unambiguous terms (Major W. J. A. O'Meara, *The Electrician*, Vol. 71, p. 762).

As regards disputes, it is not uncommon for the purchaser's engineer to be given the sole right of deciding disputed points; there are great objections to any such procedure, and arbitration is the only legitimate way of settling such questions, as the dispute may often be due to lax wording or definition of terms on the part of the purchaser's engineer in his specification or general conditions. Another clause often inserted, but liable to abuse, is the omnibus clause, laying on the contractor the responsibility of supplying, within the tendered price, everything necessary to complete the works, whether specified or not; within reason this is fair, but it may enable the purchaser to obtain, free of cost, goods which he had not thought of originally and which are not really essential. Shipping weights and dimensions should always be asked for, especially where subsequent transit over mountainous or rough country is involved. Foundation plans should also be asked for with the drawings. Wherever possible, the approved standards of the British Standards Institution (§ 1055) should be adhered to. Terms of payment should be specified; it is usual to pay about 80 % on delivery, 10 % on the setting to work and the remainder after a period of 3 to 6 months' working; in large foreign contracts a proportion is often paid on shipping documents.

1001. Specifications continued—Generators (Chap. 4).—Whatever type of generator is required, and whatever purpose it is to be used for, the purchaser should give the following details

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when asking for tenders, unless in any particular item he is willing to leave the matter to the discretion of the tenderer; in which case the latter should be asked to supply the necessary data in his tender:—

- (a) Normal full load output in kilowatts.*
- (b) Maximum overloads and duration, usually 25 % for 1 hr. and 100 % momentarily* (§ 136).
- (c) Terminal volts at full load (standard, § 23).
- (d) Whether direct coupled or, if not, how driven.
- (e) Revolutions per minute, according to drive and type of prime mover (§ 254).
- (f) Number of poles, if material to case (§§ 138, 254).
- (g) Whether for parallel running with machines already at work; if so, full description of same should be given (§§ 148 to 150).
- (h) If the neutral point or neutral wire is to be connected to earth the fact should be stated (§ 354).
- (i) Efficiency at full, $\frac{2}{3}$, $\frac{1}{2}$, and $\frac{1}{4}$ load and at 25 % over load.†
- (j) Temperature rise over surrounding air of various components, after run of 6 to 10 hrs. at full load and also after subsequent run at specified overload† immediately following ordinary test run. Also whether temperature is to be determined by thermometer or resistance (§§ 122, 1024). Maximum air temperature of locality (§ 136) should be stated in the case of plant for use in the tropics.

D.C. Machines.

- (k) Winding—series, shunt, or compound (§ 138).
- (l) Rise of pressure from no load to full load for compound-wound machines (§§ 138, 148).
- (m) Extent of required pressure variation by means of field regulation in shunt-wound machines (§§ 138, 432).
- (n) Sparkless commutation; if commutating interpoles (§ 139) are not required the fact should be stated, as they are fairly universal now.

A.C. Machines.

- (o) Number of phases—single or 3-phase generally.
- (p) Periodicity (standard 50 cycles, § 134 and Chap. 5).
- (q) Output in kVA at expected power factor (§ 157) as well as in kW at unity P.F.; the machine to conform to specified temperature rise under the conditions of the lower P.F., i.e. with the larger current.
- (r) Pressure regulation under conditions of non-inductive and inductive load, generally given at P.F. = 1 and 0.8 (§ 147).
- (s) Excitation required, and whether exciter is to be driven from the alternator shaft or separately.

Accessories.—Field regulators; cables connecting to switchboard; holding down bolts; spare parts, viz. armature coils or extra armature, brushes, and gear; bearing bushes; tools. If belt-driven, pulley, slide rails, belt tightener.

* The 'rated output' as specified by the British Engineering Standards Committee covers both (a) and (b): see §§ 136, 670.

† See, however, footnote to items (a) and (b).

1002. Specifications continued—Motors (Chap. 28).—In the case of motors the purchaser should state, or ascertain from tenderers:—

- (a) Whether open, ventilated, or totally enclosed type is required (§ 4 and Vol. 3).
- (b) Whether to be rated for continuous or intermittent working, and the normal B.H.P. on this basis (§ 670).
- (c) Maximum overload and duration, as in the case of generators.*
- (d) Terminal volts (standard, § 23).
- (e) Whether direct coupled and, if not, whether driving by belt, rope, helical gearing, worm gearing, etc. In the case of gearing the required reduction should be stated (§ 751). If ball bearings or roller bearings are required the fact should be stated.
- (f) Revolutions per minute, according to drive and type of machine to be driven; allowable limits of variation at different loads, or required speed variation as the case may be; size of driving pulley.
- (g) Number of poles, if material.
- (h) Required starting torque, if material.
- (i) Whether system on which motor is to work is connected to earth at neutral (§ 354).
- (j) Efficiency and temperature rise as in the case of generators.

D.C. Motors.

- (k) Whether series, shunt or compound-wound (§§ 138, 675-677); and whether required with commutating interpoles (§ 139), as for variable speed motors.

A.C. Motors.

- (l) Number of phases and periodicity, as in the case of generators.
- (m) Whether synchronous, commutator, or induction type, and, in last-named case, whether squirrel-cage or slip-ring (§ 681). In the case of synchronous motors, separate excitation is required, and must be arranged for.
- (n) Starting current should be stated in tender.
- (o) Power factor at full, $\frac{2}{3}$, and $\frac{1}{2}$ load should be stated in tender.

Accessories.—Starting and regulating gear; no-load and overload release; cables from motor to starter, etc.; spare parts, as in the case of generators; holding-down bolts; tools. If for belt-driving, pulley, slide rails, belt tightener.

1003. Specifications continued—Transformers (Chap. 17).—

- (a) Whether single-phase or 3-phase; periodicity.
- (b) The required output on the secondary side should be given in kW or, if the load to be supplied is inductive, in kVA. The nature of the load, or the probable P.F. at secondary terminals, should be stated (§ 157).
- (c) Pressure of supply at the primary terminals; required pressure at the secondary terminals (standard, § 23). As to star and mesh connection see § 394.

* See, however, footnote and reference in § 1001.

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- (d) Whether oil-insulated or not. Oil insulation is generally used for extra high pressures and in large sizes, where the heat generated can be carried away by water pipes in the oil space. Small transformers depend on the dielectric on the coils (§ 400).
- (e) Whether artificially cooled and (if so) whether by air or water (§ 400).
- (f) Pressure regulation at full load on P.F. of unity and 0.8 (§ 392).
- (g) Open circuit losses (§ 394, Table 53).
- (h) Overall efficiency at full, $\frac{3}{4}$, and $\frac{1}{2}$ load (§§ 394, 401, Tables 53, 54).
- (i) If special tapplings for variable pressure are required (§ 636).

Accessories.—Transformer oil; spare coils; circulating fan or pump for cooling; piping.

1004. Specifications continued—Storage Batteries (Chap. 18).—

- (a) The number of cells, including regulating cells, must be stated (§ 430) or the working pressure of the installation.
- (b) The required capacity in ampere-hours must be given. This varies with the rate of discharge (§§ 430 *et seq.*). It is usual to specify the capacity when the battery is discharged in 5 or 10 hrs. and also the maximum safe discharge current for 1 hr. Alternatively, the conditions of load and probable hours of working may be specified.
- (c) Specify by whom the stands are to be supplied, painted and erected.
- (d) Specify by whom the electrolyte is to be supplied, and exact a guarantee as to its purity (§§ 431 *et seq.*)
- (e) Ascertain the normal and maximum charging rates (§ 432).

Accessories.—Hydrometers for specific gravity; cell testing voltmeter 1.4 V; lamp to slip between plates for cell inspection; connections to switchboard; spare plate sections. Lead-burner's outfit, if necessary; tank for acid mixing; water-distilling apparatus; anti-sulphuric enamel for stands, etc. Note the E.M.F. required for cell charging (§ 432). If necessary a booster can be used (§ 432).

1005. Specifications continued—Switchboards (Chap. 16).—

- (a) The number of panels and apparatus required on each, and the normal current and pressure, should be stated, always remembering that the current of an accidental short-circuit will be enormously in excess of the working current, and is the crucial figure for circuit-breakers, etc. These may comprise the following: (i) Panel for each generator, with ammeter (reading to about double the current of the generator); voltmeter (standard pressure central on scale); main switch or circuit-breaker; cut-outs, fusible or automatic; reverse current circuit-breaker, if required; shunt regulating switch and resistance, unless placed on separate pillar; wattmeter if required. For large currents shunted ammeters (§ 107) or current transformers (§§ 107, 108, 334) may be required; and for high-pressure voltmeters transformers also (§§ 108, 334). (ii) Panel for each feeder, similarly provided (according to the load on each) with ammeter, voltmeter, switches, cut-outs. Where two sets of bus-bars are provided and kept at different potentials, change-over switches are required on generator and feeder panels. (iii) Total output panel, between generators and feeders, with ammeter and wattmeter for maximum output and also station voltmeter. (iv) Neutral panel on 8-wire systems, with centre zero ammeter to show out-of-balance current

- (§ 461). The earth connection of neutral may be taken from this panel, and a current-limiting resistance may be added if necessary to keep the earth current down. (v) Balancer panel, where balancers are used on a 3-wire system. Centre-zero ammeter and voltmeter for each side of system. Switches, starting gear, and cut-outs for balancer, and shunt regulator. (vi) Station lighting panel. (vii) Battery panel with charge and discharge regulator switches (§ 432) and centre-zero ammeter, showing charge or discharge current; automatic cut-in and cut-out.
- (b) For A.C. synchronising panel; power factor indicator. If high tension, oil switches and instrument transformers (§ 405).
- (c) For tramways, 'Board of Trade panel'; also equalising bars and switches at generators (§ 148).
- (d) Recording (chart) voltmeters may be required (§§ 93, 97).
- (e) The type of switches, instruments, etc., and material of panel and framing may be specified or left to each tenderer.
- (f) Special distant control and automatic regulators may be required; also special protective gear for excess pressure on A.C. lines (Chap. 15).

Accessories.—Connecting cables to generators, balancers, regulating pillars, line, etc.; lightning arrestors (§ 346) and choking coils; isolating switches, which can be opened up on both sides of any H.T. apparatus when the circuit is broken for repairs; oil for oil switches; clock.

1006. Specifications continued—Cables (Chaps. 13, 14).—

- (a) Specify whether for feeders or distributors (§§ 441, 442) or for trailing cables (§ 820), or for house wiring, etc.
- (b) Whether single, 2 or 3 core, or concentric, and for D.C. or A.C.
- (c) Cross-sectional area of each conductor, to be of standard copper (§§ 62, 279, and Tables 39, 40). For aluminium *see* § 63.
- (d) Working pressure.
- (e) Whether any conductor is to be connected to earth.
- (f) Class and grade of cable (§§ 281, 283).
- (g) Method of laying (§ 290).
- (h) Length of route.
- (i) Ascertain actual guaranteed insulation resistance, thickness and nature of dielectric, weight, conductor resistance—at standard temperature.
- (j) If for A.C., ascertain capacity and charging current under working conditions (§§ 307, 311).
- (k) Specify who is to lay and joint cable.

Accessories.—Jointing material; distribution boxes, disconnecting links, feeder pillars; troughing, filling and protecting material (if any).

1007. Specifications continued—Overhead Lines (Chap. 14).—

- (a) Whether solid or stranded hard-drawn copper wire; and S.W.G. (§ 307 and Table 44). For aluminium *see* § 308 and Table 45. For steel *see* § 309. For bronze, etc., *see* Table 49 in § 381.
- (b) Length of route and of wire required.
- (c) Obtain guarantee as to standard conductivity and weight; also ultimate tensile strength (§§ 62, 63).
- (d) Specify maximum electrical pressure on insulators and also mechanical stress to be carried (§ 380).

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- (e) Ascertain breaking-down conditions of insulators and pins, electrical and mechanical (§ 330).
- (f) State length and construction of brackets or cross arms (§§ 327 *et seq.*).
- (g) Number of brackets or cross arms and of insulators and pins.
- (h) Height above ground and overall length of poles (§ 323).
- (i) Type and ultimate strength of poles (§§ 324, 325).
- (j) Special poles, such as towers for long spans (§ 329), feeder junction poles, heavy terminal or angle poles, etc., to be separately enumerated as in (g) and (h).
- (k) Special strain or shackle insulators.

Accessories.—Jointing and binding material; earth wires and earth connections (§§ 324, 347); struts and stays (§ 326); anchors for stays; line lightning arrestors (§ 346); disconnecting links; safety devices and guard wires; spare parts; line-men's tools.

1008. Specifications continued—Steam Plant (Chap. 6).—

In the case of most of these sub-heads the tenderer should be allowed to specify what he considers most suitable, unless there are reasons to the contrary.

- (a) Whether for direct coupling or belt or rope drive.
- (b) Brake horse-power: or specify that each set shall be able continuously to drive its generator at the specified overload.
- (c) Vertical or horizontal.
- (d) Revolutions per minute, according to nature of drive.
- (e) Maximum momentary and permanent variation in speed when running on governor and load is thrown on or off.
- (f) Whether simple, compound, or triple expansion, or steam turbine.
- (g) Condensing or non-condensing.
- (h) Open or enclosed and method of lubrication.
- (i) Number of cranks.
- (j) Steam pressure at stop valve.
- (k) Steam consumption and mechanical efficiency at full, $\frac{1}{2}$, and $\frac{3}{4}$ load and on specified overload of generator (§ 167).
- (l) In case of combined plant, overall efficiency of sets.

Accessories.—Steam and exhaust piping and covering for same; main valve; steam traps, drain cocks, relief valves, gauges, tachometer; condenser (§ 175), air and circulating pumps, etc.; spare parts; tools.

1009. Specifications continued—Boilers (Chap. 6).—

- (a) Type—Lancashire, water-tube, marine, loco, etc. (§ 170).
- (b) Working pressure and whether superheat required or not; if so, the degree of superheat.
- (c) Fuel to be used and approximate average calorific value.
- (d) Nature of draught—natural, forced, or induced.
- (e) Steam required per hour—or it may be specified that the boilers shall be capable of steaming continuously at the rate required to obtain the maximum overload of the generating sets (§ 167).
- (f) Whether mechanical stokers are required.
- (g) The square feet of grate area, fuel consumption, and actual steaming capacity with given feed temperature should be stated in tender unless specified.

Accessories.—Safety valves; main stop valve; feed check and stop valves; blow-off valve; pressure gauge; water gauge and guards; feed pump or injector; feed water heater; economiser; oil extractor; superheater; air pre-heater; steel or other chimney stack; fan for mechanical draught; motors for automatic stoker, economiser scraper, fan, etc.; firing tools; spare fire bars and gauge glasses; pipe work and valves for main steam range and all above accessories and lagging for boilers and pipes; exhaust piping to condenser or atmosphere or to both.

1010. Specifications continued—Oil and Gas Plant (§§ 178 *et seq.*).—*See* steam plant above, § 1008 (*a*) to (*e*) being applicable here also. If the Diesel or semi-Diesel type (§ 180) is required, in preference to the ordinary oil engine, this should be made clear.

- (*f*) State altitude and maximum temperature of place where engine is to be used (§ 179).
- (*g*) State nature of fuel and average calorific value (§ 178).
- (*h*) Specify (or inquire) fuel consumption and efficiency at full, $\frac{1}{2}$, and $\frac{1}{4}$ load and at specified overload.
- (*i*) Cooling water tanks and all piping for water exhaust.
- (*j*) Fuel tanks for oil; producer and accessories for gas.
- (*k*) Silencer.
- (*l*) Starting gear when required; compressed air cylinders for Diesel type.

1011. Specifications continued—Water Turbines and Pipes (Chaps. 8 to 11).—*Wheels.*—*See* steam plant above, § 1008 (*a*) to (*e*) being applicable here also.

- (*f*) State gross and net head and quantity of water available in cusecs (§§ 201, 202).
- (*g*) Impulse or reaction wheels (§ 214).
- (*h*) Method of regulating inlet; in case of high heads whether by spear, deflector, or deflecting nozzle or 'Sewer' nozzle (§ 255).
- (*i*) Water consumption and efficiency at full, $\frac{1}{2}$, and $\frac{1}{4}$ load and overload.

Accessories.—Pressure gauge; tachometer; taper pipes from main pipe to nozzle; main valve; relief valve; governor and connections; spare parts.

Pipes (§§ 246 *et seq.*).

- (*a*) Whether each wheel will have its own pipe or whether a common pipe will be used, with a receiver.
- (*b*) Length, vertical head, and quantity of water to be carried at full and overload.
- (*c*) Diameter of pipes and loss of head at full and overload—or it may be specified that the pipes shall carry the quantity of water required, under the net head, for the specified performance of the plant.
- (*d*) Whether single or double riveted, welded, or solid drawn, and thickness and factor of safety (§§ 246 *et seq.*); or latter may be given and details left to the makers.
- (*e*) Nature of joints (§ 252).
- (*f*) Details as to dipping for protection against corrosion.

Accessories.—Bends, vertical and horizontal, from exact survey of pipe-line; expansion joints; thrust blocks; bell mouths; valves; air chambers, if necessary; strainers jointing material; spares; tools.

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1012. Depreciation.—If interest has to be paid on the balance of the capital cost of an installation at a rate r %, and depreciation is to be set aside at the end of each year at a fixed annual rate per cent. on the original cost, so as to pay off the sum (capital and interest) by the end of the presumed life, then rate of depreciation per cent. $= 100 \times r[(1 + r)^n - b] / [(1 + r)^n - 1]$, where n = years of life and b is the ratio of the value of the old material at the end of the period to original cost, expressed as a decimal. Thus, taking the rate of interest at 5 %, *i.e.* 0·05, the life as 5 years, and the value of the old material as nil.

Depreciation $= 100 \times 0\cdot05 (1\cdot05)^5 / (1\cdot05^5 - 1) = 23\cdot12$ %.
Working this out we have—

	Balance at End of Year.
Original sum	100
Interest 1st year	5
	105
Depreciation set aside at end of 1st year = 23·12, Balance	81·88
Interest 2nd year	4·09
	85·97
Depreciation at end of 2nd year = 23·12, Balance . .	62·85
Interest 3rd year	3·15
	66·00
Depreciation at end of 3rd year = 23·12, Balance . .	42·88
Interest 4th year	2·15
	45·03
Depreciation at end of 4th year = 23·12, Balance . .	21·91
Interest 5th year	1·15
	23·06
Depreciation at end of 5th year = 23·06, Balance . .	Nil.

If in this case the value of the old material had been 15 % (*i.e.* 0·15 in the equation) the rate of depreciation would be 20·4 instead of 23·06 %. From this formula the depreciation rates in the last column of Table 100 have been worked out, but in some cases alternative values (given last) have been added from various authorities.

If the rate, D %, of depreciation is known, and it is desired to ascertain the length of life assumed, the formula can be transposed. Where the value of the old material is nil we have—

$$n = [\log D - \log (D - 100r)] / \log (1 + r).$$

Thus, in the example given, we have

$$n = (\log 23\cdot16 - \log 18\cdot16) / \log 1\cdot05 = 5.$$

Where the old material has a value the expression becomes

$$n = [\log (D - 100rb) - \log (D - 100r)] / \log (1 + r).$$

In the second example therefore we have

$$n = [\log (20.4 - 7.5) - \log (20.4 - 5)] / \log 1.05,$$

which again gives 5 years.

In this connection may also be mentioned the amortisation of capital, dealt with in the *Electrical Trades Directory and Handbook*. Formulæ are there given for the four principal schemes on which a sinking fund may be constructed to cover depreciation, viz. :—

1. The annual deposits may be of equal value, or a constant percentage of the original capital outlay, and accumulate at compound interest.

2. The annual deposits may be of equal value, and the interest accruing on them applied to some purpose other than addition to the sinking fund.

3. The annual deposits may be a constant percentage of the unwritten-off capital, in which case they are of decreasing value from year to year, and accumulate at compound interest.

4. The annual deposits may be a constant percentage of the unwritten-off capital, and the interest accruing on them applied to some purpose other than addition to the sinking fund.

During periods in which the purchasing power of money varies widely, it is rational to adjust the annual monetary allowance for depreciation to correspond with the real reduction in value of the assets concerned.*

The whole question of depreciation is an extremely difficult one, and should be dealt with by the professional accountant rather than the engineer. A valuable contribution to the subject will be found in a paper on 'The Annuity or Sinking Fund Theory of Measurement of Depreciation of Plant,' by P. D. Leake, in *The Electrician*, Vol. 74, p. 856; and the whole subject is dealt with exhaustively in 'The Depreciation of Factories, Mining, Municipal, and Industrial Undertakings and their Valuation,' by Ewing Matheson, M.Inst. C.E. Annuities and sinking funds are further referred to in § 1014.

1013. Life of Plant: Depreciation, Residual Value, and Loan Periods.—The approximate life of the component parts of electrical installations, the residual value at the end, assuming

* This problem is discussed and illustrated in 'Some Common Delusions Concerning Depreciation,' by E. F. DuBrul, *Mechanical Engineering* (Amer. Soc. Mech. Eng.), May, 1928, p. 373.

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proper maintenance, and the rate of depreciation to be set may be taken as follows:—

TABLE 217.—*Life and Depreciation of Plant, etc.*

	Life in Years.	Residual Value as per Cent. of Original Cost.	Rate of Depre- ciation per Cent. of Capital Cost, Interest 5 %.
Foundations and main buildings	Indefinite	Nil	2½
Sub-station buildings . . .	50	Nil	5½ to 8
Water-tube boilers . . .	25	5	7 to 8
Lancashire boilers . . .	22	3	7½ to 10
Generators . . .	30	8	6½ to 8
Engines and other machinery . .	25	6	7½ to 10
Water turbines . . .	25	3	7½
Cables, armoured . . .	35	15	6 to 3
„ laid 'solid' . . .	40	12	5½ to 3
Accumulators . . .	10 to 15	10	9 to 12
Steel posts . . .	40	5	5½ to 2
Motors . . .	15 to 25	9	9 to 7½
Traction motors . . .	10 to 15	10	12 to 9
Arc lamps . . .	12	5	11
Meters, instruments, etc. . .	12	2	11½
Tools . . .	10	5	12½
Tramway track (but see § 901) . .	10 to 15	5	12½ to 9
Sub-station equipment . . .	25	12	

The bare copper wire of overhead mains and transmission lines may be taken to last indefinitely; its value as scrap may be more than its original cost. The above data are based on wide practical experience and may be taken for estimating purposes where private investment is concerned. In the case of municipal expenditure, however, in respect of which loans are raised under the sanction of the Local Government Board, the periods laid down by that authority for the repayment of municipal loans must be observed. Generally these periods are much shorter than the actual life of the plant. Whilst conservation is a reasonable policy where public investment is concerned, it is easy to go too far in this direction and impose a heavy handicap on the profitable operation of new equipment by requiring unnecessarily rapid repayment of its cost.

In this connection reference may be made to correspondence between the I.E.E. and Local Government Board in which the former body sought to extend the repayment periods allowed on loans for cables, conduits, storage batteries, and reinforced concrete. The old L.G.B. allowances, the I.E.E. proposals, and the new L.G.B. figures may be thus summarised (*see also Jour. I.E.E.*, Vol. 54, p. 63):—

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Loans on—	Old L.G.B. Periods. Years.	I.E.E. Proposals. Years.	New L.G.B. Periods (August, 1915). Years.
Cables, laid 'solid' in ducts . .	25	30	25
„ armoured, laid direct . .	15		
„ armoured but coated with jute and bitumen and covered with bricks . .	20		
Conduits	—	60	25 to 30
Storage batteries	5	15	7
Reinforced concrete	15	30	15 (variable with character)

The Electricity Commissioners allow the following periods for the repayment of loans sanctioned by them, *viz.* :—

Freehold land	60 years.
Leasehold land	30 „
Buildings	30 „
Plant and machinery	20 „
Trunk mains	40 „
Other mains and service lines	25 „
Meters	10 „
Internal wiring	10 „
Apparatus let on hire	7 to 10 „

Except for internal wiring, which ought to last far longer, these rates are reasonable. The period of 20 years allowed by the Commissioners for plant and machinery has, however, often been reduced to 15 years as a maximum in cases where there was reason to anticipate that generating plant was specially liable to be superseded, owing to the probability of bulk supply or otherwise (First Annual Report, p. 28). Having regard to the changed conditions brought about by the Act of 1926 the Commissioners came to the conclusion that a repayment period of 15 years in such cases must now be regarded as too long for general application; and that cases would arise in which it would be difficult to justify a longer period than 10 years (Seventh Annual Report, p. 76).

Into the questions of Income Tax and Fire Insurance, both of which are affected by depreciation and by obsolescence, it is not possible to enter here. The whole question of depreciation, of obsolescence and of loan repayment periods is in a state of constant

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flux; it forms a perennial topic of discussion in the technical Press, to which the reader may be referred for further light on it.

1014. Provision for Loan Repayments.—Further to the notes in the preceding paragraph, it may be pointed out that although plant may actually last many years it will inevitably become out of date before it is actually worn out, and replacement then becomes commercially sound. It is preferable therefore that a loan should be repaid completely by the time that it will probably pay to replace the plant, in which case the repayment of the capital takes the place to some extent of the depreciation fund of a limited company. There are two usual methods for the repayment of loans, apart from sinking funds, *viz.*: (1) by equal yearly or half-yearly portions of principal, with interest on the balance from time to time outstanding, known as the ‘instalment method’; and (2) by equal yearly or half-yearly payments to include interest and principal known as the ‘annuity method.’ Both are considered preferable to a sinking fund. By the instalment method the payments decrease in amount as time goes on, whereas by the annuity method they are of equal amount throughout the term; under the same conditions of interest and period the total payments are therefore slightly greater with the latter method, though it is more often adopted.

It will be useful here to note a few facts and formulæ covering the usual methods of dealing with annuities, sinking funds, etc. All are based on the ordinary geometrical progression of the type

$$a + aR + aR^2 + aR^3 + \dots$$

in which the n th term is aR^{n-1} , and the sum of the first n terms is a

$$(R^n - 1) / (R - 1).$$

The following formulæ are derived from these:—

- (1) Amount, at the end of n years, at $100r\%$ interest, of an annuity of $\pounds N$ per annum

$$= N\{(1 + r)^n - 1\} / r.$$

- (2) Debt repayment by the annuity method:—

If a debt of $\pounds 1$ is to be paid off by n equal payments made to the creditor at the end of every year from the 1st to the n th inclusive, the amount of each yearly payment ($\pounds N$) is given by

$$N = r(1 + r)^n / \{(1 + r)^n - 1\},$$

where $100r\%$ is the rate of interest on the unpaid balance of the debt in each year.

- (3) Debt repayment by Sinking Fund:—

In this case the debtor sets aside an amount $\pounds N$ at the end of each year, which accumulates at (say) $100r\%$ interest. Meanwhile the debt accumulates at $100R\%$, and N must be such that at the end of the n th

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year, when the n th amount has been set aside, the accumulated total of the Sinking Fund equals the accumulated total of the debt. This gives

$$3(a) \dots N = r(1 + R)^n / \{(1 + r)^n - 1\}.$$

If $R = 0$, this formula gives the case of a sinking fund required to provide £1 at the end of n years without paying interest on capital, in which case

$$3(b) \dots N = r / \{(1 + r)^n - 1\},$$

while if $r = R$, this method of debt repayment gives results identical with the annuity method, viz. :—

$$3(c) \dots N = r(1 + r)^n / \{(1 + r)^n - 1\}.$$

If r is greater than R , the Sinking Fund method will be the cheaper of the two, and vice versa.

It is further worth noting, in order to make the best use of any tables that may be at one's command, that

- (4) The plain Sinking Fund payment N in 3(b) above is the reciprocal of the amount of an annuity of £1 p.a. in (1) above.
- (5) The amount N in (2) above exceeds that in 3(b) by r .

The following table, condensed from Inwood's (*Schooling*) Tables and J. A. Archer's tables for the repayment of loans, covers the

TABLE 218.—*Repayment of a Loan of £100 by Annuity.*

Years of Repayment.	Annual Payment; Rate of Interest being—							
	3½ %.	3¾ %.	4 %.	4¼ %.	4½ %.	4¾ %.	5 %.	6 %.
5	22·148 1	22·305 2	22·462 7	22·620 7	22·779 2	—	23·097 5	23·739 6
7	16·354 4	16·507 5	16·661 0	16·815 2	16·970 1	—	17·282 0	17·913 5
10	12·024 1	12·176 1	12·329 1	12·483 0	12·637 9	—	12·950 5	13·586 8
15	8·682 5	8·837 6	8·894 1	9·152 0	9·311 4	—	9·634 2	10·296 3
20	7·036 11	7·196 21	7·358 17	7·521 98	7·687 61	7·855 05	8·024 26	8·713 5
21	6·803 66	6·964 86	7·128 01	7·293 08	7·460 06	7·628 91	7·799 61	8·500 5
22	6·593 21	6·755 53	6·919 88	7·086 23	7·254 56	7·424 85	7·597 05	8·304 6
23	6·401 83	6·565 34	6·730 91	6·898 55	7·068 25	7·239 97	7·413 68	8·127 8
24	6·227 23	6·391 89	6·558 68	6·727 63	6·898 70	7·071 87	7·247 09	7·967 9
25	6·067 40	6·233 17	6·401 20	6·571 45	6·743 90	6·918 51	7·095 25	7·822 7
26	5·920 54	6·087 47	6·256 74	6·428 31	6·602 14	6·778 19	6·956 43	7·690 4
27	5·785 24	5·953 34	6·123 85	6·296 74	6·471 95	6·649 44	6·829 19	7·567 9
28	5·660 26	5·829 54	6·001 30	6·175 49	6·352 08	6·531 02	6·712 25	7·459 3
29	5·544 54	5·714 99	5·887 99	6·063 50	6·241 46	6·421 83	6·604 55	7·353 0
30	5·437 13	5·608 76	5·783 01	5·959 82	6·139 15	6·320 94	6·505 14	7·264 9
40	4·682 7	4·865 9	5·052 3	5·241 8	5·434 3	—	5·827 8	6·646 2
50	4·263 37	4·457 42	4·655 02	4·856 00	5·060 21	5·267 49	5·477 67	6·344 4

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ordinary periods of repayment and rates of interest in connection with electrical engineering works. The figures in each case represent the equal annual payments of principal and interest on a loan of one hundred pounds, to be extinguished in the period given, on the annuity system.

If the payments are made half-yearly they are slightly less than half the amounts shown by this table, but for project purposes this may be neglected.

The total amount payable for interest by the *annuity method* is found by deducting the principal from the total payment. Thus in the case of a loan of £10 000 repayable by 20 equal annual instalments at $4\frac{1}{2}\%$, the table shows that each payment will be £768·761* or in all £15 375·22, of which interest therefore accounts for £5 375·22.

If the *instalment method* is used the total interest charges are found by multiplying the interest on the loan for one year by the number of years in the period increased by one, and dividing the product by two. Thus, in the same example: Interest on £10 000 for 1 year is £450; and period is 20 years. Hence total interest = $£450 \times 21/2 = £4 725$, and the total repayment will be £14 725.

With the *sinking fund method* for the case of $r = R = .045$, the amount to be set aside is, by 3 (a) and (b) above, the same as that required with the annuity method, *viz.*: £768·761. If full tables are not available, this figure can, *vide* (5), be found from a plain sinking fund table [3(a)] by adding r (note that this only applies if $r = R$). Thus a plain S.F. table for the case considered gives

£0·031 9 per £1 (approx.),

adding $r = 0\cdot045\ 0$

gives $\underline{\hspace{1cm}} \quad \underline{\hspace{1cm}} \quad \underline{\hspace{1cm}}$
£0·076 9 per £1 or £769 per £10 000.

Further, the plain S.F. amount can, *vide* (4), be derived if necessary from an annuity table; thus

Amount of £1 p.a. for 20 years at $4\frac{1}{2}\%$ (from tables or formula (1)) = £31·4

Hence plain S.F. yearly payment = $\frac{1}{31\cdot4} = £0\cdot031\ 9$ per £1 as above.

* By formulæ (2) above $N = 10\ 000 \times .045 \times 1\cdot045^{20} / \{1\cdot045^{20} - 1\}$.

1015. Maintenance.—The rates of depreciation given above assume that the plant, etc., is properly looked after. During the earlier years the cost of maintenance is very small, but it goes on increasing with time; an average rate of $2\frac{1}{2}\%$ on buildings and 4% on plant may be debited to this head. As regards the internal wiring of buildings no depreciation need be set aside; cases have occurred where the insulation on the wires has become useless after a very few years, either from climatic effects, damage by white ants, or electrolysis, but as a rule circuits can be replaced as required out of maintenance, and the life of the installation prolonged almost indefinitely. It has been found in India that an average maintenance rate of $4\frac{1}{2}$ to 5% covers this fully, and in temperate climates it will be far less.

As regards overhead lines, on one large system abroad the average cost of maintenance over 4 years worked out at £7 per mile per annum; this included painting the poles and repairing damage due to storms and falling trees. The life of a coat of good metallic paint is about 3 years, but difficulty has been experienced in finding a paint which will withstand a tropical climate.*

1016. Bibliography.—(See explanatory notes, § 58, Vol. 1.)

OFFICIAL REGULATIONS.

See Chapter 41 in this volume.

All specifications must be consistent with official regulations enforced in the districts where material, apparatus, etc., is to be used; they should also take account of the I.E.E. Wiring Rules or other schedules which, though not enforced by law, are representative of good practice.

STANDARDISATION REPORTS, ETC.

B.S.I. Publication No. 205.—Glossary of Terms used in Electrical Engineering.

All specifications should, wherever possible, be consistent with I.E.C. publications and B.S.I. specifications; references to these are given in the bibliographies at the end of each chapter in this work, but fresh publications are continually being issued, full particulars of which can be obtained from the offices of the I.E.C. and B.S.I. at 28 Victoria Street, London, S.W. 1.

BOOKS.

Specification and Design of Dynamo-Electric Machinery, M. Walker (Longmans, Green).

Electrical Engineering Economics, D. J. Bolton (Chapman & Hall).

Economic Tables for Electrical Engineers, D. J. Bolton (Chapman & Hall).

Depreciation of Factories and their Valuation, E. Matheson (Spon).

Engineering Economics, T. H. Burnham (Pitman).

* Aluminium paint appears to be fairly satisfactory.

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I.E.E. PAPERS.

Principles Involved in Computing the Depreciation of Plant, F. Gill and W. W. Cook. Vol. 55, p. 187.

Engineering Specifications, J. Shepherd. Vol. 55, p. 363.

(The reviews of progress issued periodically by the I.E.E. contain valuable information on standardisation and specification. See, for example, Standardisation, P. Good. Vol. 64, p. 495).

MISCELLANEOUS.

I.E.E. Form of Model General Conditions for Contracts.

I.E.E. Standard Clauses for Street Lighting Specifications.

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Depreciation of Steam Plant, S. Howard Withey. *The Steam Engineer*, Vol. 2, pp. 263, 358. (Explaining different methods of allowing for depreciation, and presenting typical examples of the necessary calculations and book entries.)

CHAPTER 40.

TESTING.

1017. Performance of Electrical Machines.—The aim of the designer of electrical apparatus is efficiency in the broadest sense; this includes the narrower conception of the ratio of output to input, together with such factors affecting fitness for service as insulation, regulation and polarity. Efficiency, *per se*, is settled by the losses separately; in general they comprise copper and iron losses, friction and windage. The temperature reached by an electrical machine depends upon the magnitude of the copper and iron losses, the emissivity of the surfaces and the amount of heat abstracted by the ventilating air currents. It is possible to predetermine the actual temperatures to be attained in different parts of a machine with some accuracy, but since the life of insulating materials may be short (§ 80, Vol. 1) if the temperature be too high at the hottest spot, tests are undertaken to see that the anticipated performance is achieved.

1018. Insulation Tests.—Insulation resistance measurements as applied to cables are considered in § 119, Vol. 1, and § 470, Vol. 2, and similar procedure is applicable to machines. Machinery windings are not usually enclosed in lead sheaths, however, and their insulation is somewhat hygroscopic; they therefore have to be dried out before being put into use. Drying out may be finally done on site either by heating elements or by circulating currents through the windings (§ 403, Vol. 2), but initial drying out at the makers' works is usually done in special heating chambers. After baking at a temperature below the boiling-point of water (say 90° C.) in a vacuum the windings are impregnated with varnish, and after drying are then ready for the high voltage test specified by the British Standard Specification applicable to the class of machine in question. Before the high voltage test an insulation test is taken by an ohmmeter (§ 120, Vol. 1). After transit and sometimes through lack of use a machine may show less than this

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insulation resistance. If appreciably below the standard a further drying out is necessary. In such a case the resistance will probably fall further as drying commences, and it may remain very low for some hours. After a time, however, the insulation resistance will gradually rise, unless the material has been quite spoilt, and drying should be continued until a steady state has been reached at a figure reasonably near that initially specified. High voltage tests should not be applied to other than new machines at the values provided in Standard Specifications.

B.S. Specifications differentiate between four classes of insulating materials. Class O comprises unimpregnated textile materials; Class A is similar after impregnation with varnish or oil; Class B consists of mica and similar material built up by the aid of varnish or other binder; and Class C covers mica, etc., without binder, and ceramics. (See §§ 70 *et seq.*, Vol. 1, particularly § 74.)

According to B.S.S. No. 168 (1926) the insulation resistance of a motor or generator, when tested at 500 V, must not be less in megohms than

$$\frac{\text{Rated volts}}{1000 + \text{Rated output in kVA or B.H.P.}}$$

Higher values should not be specified, as their achievement may involve prolonged baking at a high temperature, leading to permanent damage to the insulation. High voltage tests of motors and generators are as follows:—

1 to 3 B.H.P., kW or kVA per 1 000 r.p.m.	1000 V + twice working voltage
3 B.H.P., kW or kVA per 1 000 r.p.m. and above	with a minimum of 2000 V.

Special voltage tests are specified for particular parts, *e.g.* field windings. Non-reversing induction motor rotors are tested with 1000 V + twice the maximum voltage that could be induced therein; reversing motors with 1000 V + four times the voltage between slip-rings at standstill on open circuit with full primary voltage on the stator windings. Supplementary high voltage tests on site are limited to 75 % of these figures. A temperature rise of 40° C. is permitted for the windings of all motors except those totally enclosed; the latter are permitted a 50° C. rise, and the commutators a further 5° C. rise in each case. Efficiencies, however, must be stated as at 75° C. Type tests, with abbreviated tests on each similar machine, are permitted up to about 50 H.P. per 1 000 r.p.m., but each individual must undergo a high voltage test. (See also § 670.)

1019. No Load Tests.—A machine whose insulation is satisfactory can be tested for performance in accordance with each of its designed functions. In the nature of things the first step is a no-load run, and this will give considerable information regarding the machine's characteristics. Before running rotating machinery it is necessary to check clearances and arrange suitable bearing lubrication, barring the rotor round by hand to ensure that it is all clear. The speed may then be brought slowly up to full rated speed in the case of a generator, or the starter operated cautiously

in the case of a motor. A converter may be considered as a motor initially. A transformer can normally only be switched straight on, on one side.

In conducting a no-load test on a generator the excitation should be slowly built up, taking frequent simultaneous readings of the field current and terminal voltage, at constant rated speed. If the speed cannot be held quite constant, simultaneous observations of speed and voltage should be taken, and the voltage corrected to the nominal speed by simple proportion. Thus if the correct speed is 100 r.p.m. and the actual speed is 105 r.p.m., then the volts, if observed to be 210, would be corrected to 200. A curve plotted from these readings gives the 'open-circuit characteristic' of the generator; this is also called the 'magnetisation curve.' In some cases it may be practicable to measure also the power required to drive the generator, both unexcited and excited; the former represents almost wholly windage, journal and brush friction. The power taken by a motor on no-load represents these factors plus excitation and iron losses, but as an approximation the no-load consumption of a motor is often taken to represent the iron losses only. If the motor is a variable speed machine the speed should be measured against field current (D.C.), rotor resistance or brush position (A.C.). The no-load current of a transformer is almost wholly absorbed by the iron losses, and thus a no-load test gives an important factor directly; this is because the magnetising current is in most cases so small that its I^2R losses in the conductors (copper losses) can be neglected.

1020. Short-Circuit Tests.—These are usually applied only to A.C. machines, since they do not serve as a reliable guide to the commutating performance of D.C. machines owing to the lower voltages necessarily employed. An alternator is tested by arranging a short-circuit through a current transformer or transformers across its terminals, running at normal speed and observing excitation and generated current simultaneously up to the full-load value of the latter. For a 3-phase machine the short-circuit current in each phase should be taken and the mean value plotted. The increase in power required to drive the alternator under test between no-load and full short-circuit current gives an approximate measure of the copper loss at full load, since the magnetic loading of the iron circuit is very light and therefore the iron losses may be neglected. From the open-circuit and short-circuit curves the excitation current

required for any load conditions can be approximately inferred by the graphical construction given in Fig. 415. Here OI is the excitation at normal voltage and no-load; OX is the exciting current to give the full-load current on short-circuit, and IX will be the exciting current for full load at full voltage. For power factors other than unity, set off OX_1 at the angle of lag or lead, and read off on IX_1 .

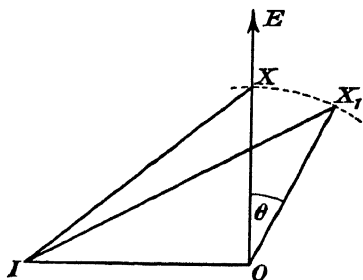


FIG. 415.—Variation of excitation current with load.

More accurate calculations take into account the additional excitation required (1) because of the higher

saturation of the iron circuit on load due to the necessity of a greater internal voltage to overcome the reactance and resistance drop in the conductors; and (2) because of the greater leakage from pole to pole with this higher saturation. If these factors be known from the design data it is possible to determine the 'regulation' of an alternator from the short-circuit and no-load curves.

Transformer short-circuit tests are generally taken with the l.t. winding short-circuited. With normal frequency the voltage applied to the h.t. winding is gradually increased until full-load current is taken; the power input is then observed and represents the total copper losses in both primary and secondary, including both I^2R and eddy losses in conductors. At the same time the voltage across the windings gives a measure of the impedance voltage of the transformer. With high impedance transformers, such as those often used with rotary converters, the power input will include an appreciable magnetising current loss. This may be measured by repeating the test with the short-circuit removed; the open-circuit loss should then be subtracted from the total. Variable pressure for these tests may be obtained by alternator excitation control or by the use of an induction regulator.

Induction motor short-circuit tests are taken with the rotor held stationary and short-circuited, a low voltage being applied to the stator windings at normal frequency and increased until full-load (or overload) current is passed. In these circumstances the iron losses are negligible, and the watts taken may be considered as the copper loss at the load corresponding to the current rating. This test, taken together with a no-load test, gives the information required for the construction of a circle diagram. The no-load test is

taken with the rotor running with no external load; the rotor losses are then negligible and the watts absorbed will represent the iron losses, which are practically constant at all loads for a given voltage and frequency. The watts divided by the voltage gives the watt-component of the current, whence the magnetising current can be readily calculated.

1021. Efficiency Tests.—Tests taken under load provide information about the operating characteristics of plant, *e.g.* the efficiency, regulation, temperature rise, etc. In the case of transformers the loads, both input and output, can be measured electrically, but with generators and motors the input and output respectively are mechanical. Since mechanical power measurements are generally less convenient and less accurate than corresponding electrical measurements it is preferable to calculate efficiency by the summation of losses method. The measurement of losses also involves smaller quantities, each of which can be observed more accurately than can the gross amounts.

$$\text{Generator efficiency} = \frac{\text{Output}}{\text{Output} + \text{losses}}$$

$$\text{Motor efficiency} = \frac{\text{Input} - \text{losses}}{\text{Input}}$$

B.S.S. No. 269 (1927) provides that efficiency measurements shall be made at or referred to a temperature of 75° C. Four classes of losses in motors and generators are recognised: (1) In the exciting circuit there are I^2R losses in the shunt field, in the main rheostat, and the actual excitation loss. (2) Fixed losses include core loss, bearing friction, total windage loss, and brush friction loss. (3) Direct load loss comprises I^2R loss in armature windings, I^2R loss in series windings, and electrical losses in brushes. (4) Stray load losses occur in iron, conductors, and brushes; they are due to changes in flux distribution caused by loading; exact values cannot be accurately estimated but they are of the order of 1½ % at full load (continuous maximum rating) for uncompensated machines, and ½ % for compensated machines.

Although special resistances, especially water tanks and troughs, have been used to dissipate the energy generated by dynamos and alternators on test, for all large generators some form of the Hopkinson back-to-back method is desirable and usual. Rough check tests can be carried out with the machines delivering to a commercial load. The back-to-back method is easiest when duplicate machines are available, but can be arranged in other conditions. If two like machines are used they are coupled mechanically and one is run as a motor driving the other as a generator, feeding back to

the driving motor. Losses can be supplied either electrically or mechanically through a motor whose efficiency curve is known.

D.C. generators are generally connected for the Hopkinson test in parallel with each other and with a source of supply of the same voltage. The field strength of one is weakened, causing it to tend to increase in speed; that of the other is strengthened, causing its voltage to rise. A circulating current is thus established between the machines, its magnitude and the speed of the combination being controlled by manipulation of the field rheostats. The power imported into the circulation from the mains indicates the losses involved in both machines, so that the efficiency of either can be readily ascertained, assuming, as is very nearly correct, that since the machines are almost equally loaded the total losses are equally divided between them. If no supply of suitable voltage is available, a mechanical drive from a calibrated motor can be used, similar arguments being applicable. In comparatively rare cases the machines may be run in series with a booster suitable for giving their rated current at a low voltage; again, the power supplied in this way is a measure of the losses of the machines.

The Hopkinson principle is also applicable to A.C. machines, but in this connection a manipulation of the excitations causes only a circulation of current out of phase with the voltage, without a power component. For some purposes, such as heat runs, that suffices, but if an actual circulation of power between the machines is desired they must be mechanically coupled with an angular displacement between their field systems, or with one frame displaced radially in relation to the other. The necessary displacement varies with the design and the amount of load to be circulated, but will be of the order of 25 electrical degrees for full load. Manipulation of the excitations of the two machines will in addition permit the power factor of the circulated current to be varied within wide limits. Losses can be supplied either in parallel at full voltage or in series at low voltage, as in the corresponding D.C. case. Generally, however, it is more convenient to supply the losses mechanically through a D.C. motor, since this simultaneously provides a ready means of running up to speed.

Transformers of the same design can also be tested back-to-back, the general method being to supply both low-tension windings from the same source and to connect the high-tension windings in opposition. In order to cause a circulating current to flow, the high-

or low-tension tapplings on one transformer only are changed, or else a boosting transformer is inserted in series with one of the low-tension windings.

An analogous method is available for the testing of duplicate motor-generators, rotary converters or motor converters. Generally the supply will be on the A.C. side and the machines can be arranged to circulate current on the D.C. side (through the D.C. bus-bars, if permanently erected).

When duplicate apparatus is not available a machine may be loaded back on to several others in parallel, but the calculation of the losses becomes more complicated. If even this is impracticable, and in the case of small sets, arrangements must be made for the dissipation of the energy handled. A water resistance is convenient in many cases. For the loading of motors several excellent brakes are available, but these require cooling water. Even a 10 H.P. motor dissipates approximately 425 B.Th.U. / min., *i.e.* raises 1 gallon of water per min. through 42.5° F. Both for motors and dynamos re-generation is therefore much less wasteful, since only losses are dissipated.

When none of these methods is applicable, as for example in the case of single large turbo-alternators, recourse must be had to wattless loading. The machine may be driven by a D.C. motor of relatively small size, and arranged to feed another or several machines, also motor driven and synchronised together. With the excitation of the fed machines reduced, and that of the machine under test somewhat higher than normal in order to maintain normal volts, wattless current may be circulated up to the full kVA loading of the set. The fed machines act as self-cooling chokes, and the power required is only that necessary to supply the total losses. In the machine under test the I^2R losses are those of full load, but the rotor is slightly overloaded. By measuring the volume and temperature of the ventilating air a determination of the machine's total losses can be made, and by means of embedded thermo-couples the internal temperatures measured. Certain manufacturing firms have constructed special large oil-immersed reactors for wattless tests.

1022. Regulation Tests.—Given that sufficient power and the means to dissipate it are available, the experimental determination of the regulation of a generator, either A.C. or D.C., does not present any difficulty. Regulation 'down' (§ 147, Vol. 1) can be ascertained by setting the excitation to that necessary for normal volts at

no-load and then applying full load. The drop in voltage, expressed as a percentage of normal voltage, is the Regulation 'down.' With full load still applied, increase the excitation sufficiently to give full volts and then remove the load. The difference between the open circuit voltage thus obtained and the normal voltage, expressed as a percentage of the latter, is Regulation 'up.' It will be necessary in each case to regulate the speed to normal, but the tests also provide an opportunity, when carried out with the associated prime-mover, to check the regulation of the speed governor.

1023. Heat Runs.—Of all performance tests, those to determine the temperature attained in operation are perhaps the most important. Any tendency to excessive heating must involve a reduction in the rating of the plant and thus increase its cost. The maximum temperature allowable depends on the material being heated, and, since several kinds of material are employed in electrical machinery, that part which first reaches a given temperature may impose a limit to the capacity of the whole apparatus which could be safely exceeded by other parts. The limit of capacity may be actually set by the approach of any local spot to the maximum temperature for its material. Only in rare cases does the mean temperature of a machine approach the maximum hot spot temperature, and the point of maximum temperature is usually inaccessible, even if its location is known in advance. Thermo-couples built into machines sometimes give valuable information regarding hot spots; in other cases, *e.g.* transformers, a thermo-couple located in the hottest part of the oil is surrounded by a special winding having the same thermal characteristics as the main winding and carrying a current proportional to the load.

1024. Temperature Measurements.—Three methods of measuring temperature in electrical machinery are recognised in British Standard Specifications, viz.: (a) Thermometer method, (b) Resistance method, and (c) Embedded temperature detector method. The following notes summarise these methods, but the complete text must, of course, be read for the purposes of complying with the Specifications.

Thermometer Method.—When the thermometer is used it should be applied to the hottest accessible surfaces of the stationary parts of the machine during the test period, and other thermometers should be applied to the accessible surfaces of the rotating parts as soon as the machine is stopped after the test.

The term 'thermometer' here includes mercury and alcohol bulb thermometers. When bulb thermometers are employed in places where there is any varying or

moving magnetic field, alcohol thermometers should be used in preference to mercury thermometers, as the latter are liable to read high owing to the heating effects of eddy currents induced in the mercury.

In all cases the bulb of the thermometers, except at the point of contact, should be covered with a pad of felt, cotton wool or other non-conducting material $\frac{1}{8}$ -in. thick, extending at least $\frac{3}{4}$ -in. in every other direction from the bulb, and pressed into contact with the surface to which it is applied to prevent loss of heat by radiation and convection from the bulb.

Resistance Method.—In this method the mean temperature rise of the windings is determined by the increase in resistance of the windings themselves. As a check, thermometers should be applied to the accessible surfaces of the windings to ascertain whether there is any higher local temperature. The highest of the temperatures thus found should be taken as the temperature by the resistance method. The temperature of the windings as measured by thermometer before commencing the test should not differ from that of the cooling medium, i.e. usually the ambient atmosphere. The initial resistance and initial temperature of the windings should be measured at the same time.

Since the resistance of copper over the range in question varies in direct proportion to the temperature (above minus 234.5° C.) the ratio of hot to cold temperature may be obtained from the ratio of the resistances by the formula

$$\frac{R_2}{R_1} = \frac{T_2^\circ \text{C.} + 234.5}{T_1^\circ \text{C.} + 234.5}$$

where

R_2 = Resistance of windings hot, ohms.

R_1 = Resistance of windings cold, ohms.

T_2 = Temperature of windings hot, °C.

T_1 = Temperature of windings cold, °C.

The following precautions require attention :—

(a) When measuring the temperature rise of machine windings by increase of resistance as a commercial test, more than commercial accuracy is required if accurate deductions of temperature are to be obtained. The temperature coefficient of increase of resistance of copper for 1° C. rise is approximately 0.4 %, so that instruments must read within this percentage if the temperature is to be deduced within 1° C. The determination of the resistance therefore to the third significant figure does not always determine the temperature to within 1° C. For instance, if the resistance of a coil is about 1 ohm, its resistance at a higher temperature, in order to determine that temperature with accuracy, must be measurable down to four-thousandths of an ohm.

(b) In order to determine temperatures of the windings when hot, an accurate measurement of resistance and associated temperature must be taken when the windings are cold. Special precautions should be taken in the case of large machines in view of the inaccessibility of the windings and the possibility of unequal temperatures in different parts of the machine. These cold readings should, therefore, be taken after the machine has been standing for some time, so that it may have assumed the temperature of the surrounding atmosphere. With large machines this length of time may quite well be 24 hrs. or longer, and in engine-rooms which are subject to fluctuations of temperatures further precautions will be necessary.

(c) In the case of rotor windings the resistance of the brush contact is appreciable and should be eliminated from the measurement of the resistance of the windings. In order to do this a special brush should be used which is insulated from the

rest of the brush gear and serves only to carry the small voltmeter current from the ring surface.

Embedded Temperature Detector Method.—‘Embedded temperature detectors’ are resistance thermometers or thermo-couples (§ 122, Vol. 1) built into the machine during construction at points which are inaccessible when the machine is completed; the term does not include the necessary measuring instruments. When the internal temperature of a machine is to be measured by this method, at least six detectors should be built into the machine, suitably distributed around the circumference within the slots, all reasonable efforts consistent with safety being made to place them at the various points at which the highest temperatures are likely to occur. When the winding has more than one coil per slot, the detector is placed between the upper and lower coils in a slot; in the case of a winding with only one coil per slot, the detector is placed between the outside of the coil and the inside of the slot lining at the bottom of the slot.

Measurement of Temperature of Cooling Air.—In general the temperature of the cooling air should be measured by means of several thermometers placed at different points round and half-way up the machine and at distances of from 3 to 6 ft. away from it. These thermometers should be so placed as to indicate the temperature of the current of air flowing towards the machine, and should be protected from heat radiation and stray draughts.

If the air is admitted to the machine through a definite inlet opening or openings (as, for instance, in the case of induced draught or forced draught machines), the temperature of the cooling air should be measured by means of thermometers placed in the current of incoming air near its entrance to the machine.

The value to be adopted for the temperature of the cooling air during the temperature test is the mean of the readings of the thermometers mentioned above, taken at equal intervals of time during the last quarter of the duration of the test. In order to avoid errors due to time lag between the temperature of a large machine and the variation in the temperature of the cooling air, all reasonable precautions must be taken to reduce these variations and the errors arising therefrom.

Time at which Temperatures are to be Taken.—The temperature of a machine should, whenever possible, be taken during working as well as after stopping the machine, the highest temperature thus obtained being adopted. When successive measurements show increasing temperatures after shutting down, the highest value should be taken. In the case of rotating parts, if the interval between the cutting off of the power and the machine coming to rest is considerable, suitable corrections must be applied so as to obtain as nearly as practicable the temperature at the instant of shutting down.

Measurement of Surface Temperatures.—The absorption of heat by a cold thermometer bulb applied to a hot surface causes a local drop in the temperature of the latter, and if the material concerned be of a low thermal conductivity, *e.g.* cotton insulation, it may be 5 mins. or more before the correct surface temperature is indicated. Mercury thermometers with flattened bulbs and reflecting screens, designed for more or less continuous application to hot surfaces, are liable to cause local overheating when applied to material of low thermal conductivity; the thermometer reading may then be appreciably higher than the temperature of the surface in the absence of the thermometer. Though the accuracy obtainable with mercury thermometers is sufficient for many commercial purposes, the use of thermo-couples is preferable for laboratory measurements or for special tests.

As regards *temperature correction for altitude*, when a machine intended for service at altitudes between 3 300 ft. and

10 000 ft. is tested near sea-level, the limits of temperature rise for the test as given in Table 112, § 670, shall be reduced at the rate of $1\frac{1}{2}\%$ for each 1 000 ft. above sea-level at which the machine is intended to work in service. The correction shall not be applied for altitudes below 3 300 ft.

1025. Heating and Cooling Curves.—In normal testing practice, efficiency and other tests will be combined with a heat run, the temperatures attained at the end of a specified time carrying a specified load being ascertained by the methods outlined above. In some cases electrical apparatus is short-time rated, *i.e.* is intended for duties varying in more or less definite cycles. Such equipment includes crane and lift motors, rolling mill motors, some traction motors, etc. It would be inconvenient to reproduce the specified cycle at length in the test shop, and the better method is to plot heating and cooling curves, from which it is possible to infer with safety whether or not the equipment complies with the specification. These curves are also useful in other connections, for by their aid it is possible to predetermine the maximum steady temperature that would be reached by a machine without actually loading it sufficiently, or for a sufficient time, for that state to be attained. The method is approximate only in that its calculations are based on the assumption that the heated body is heated uniformly and radiates heat uniformly; it would be strictly correct, therefore, if applied to a vessel containing water, well stirred, but it is subject to minor and irregular inaccuracies as applied to a machine such as a motor.

Referring to Fig. 416, the excess temperature above ambient temperature is plotted as ordinates and time as abscissæ. After starting heating, the excess tem-

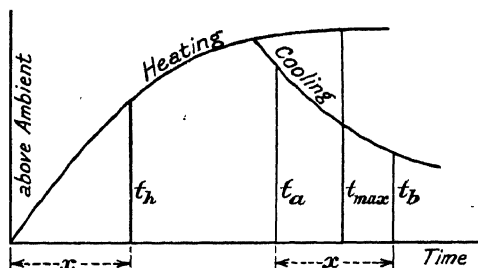


FIG. 416.—Heating and cooling curve.

perature, t_h , is read at the expiry of time x . It is again read, t_a , at any time after heating has been stopped, and again, t_b , at a time x (equal to the x interval during heating) after t_a .

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Then

$$(t_{\max} - t_h) / t_{\max} = t_b / t_a$$

whence

$$t_{\max} = t_a t_h / (t_a - t_b).$$

Also, if P be the power in watts and k the radiation coefficient,

$$k = 0.238 P / t_{\max}.$$

If M be the water equivalent of the body tested,

$$M = 0.238 P / t_{\max} \cdot \left(\frac{2.3}{x} \log_{10} \frac{t_a}{t_b} \right).$$

If p be the heating time constant,

$$p = \frac{M}{k}.$$

The time taken to reach a fraction, n , of the final excess temperature is

$$x_n = 2.3 p \log_{10} \frac{1}{1-n}.$$

The equation for the heating curve is

$$t_h = t_{\max} \cdot \left(1 - 1 / e^{\frac{1}{p} x} \right).$$

The equation for the cooling curve is

$$t_b = t_a / e^{\frac{1}{p} x}.$$

1026. Location of Faults in Machines.—Faults in electrical equipment generally originate through a failure of insulation. Since most electrical systems are earthed either deliberately or through the existence of some other fault an insulation failure leads to a short-circuit and should be followed by the operation of the circuit fuses or circuit-breakers, thus isolating the faulty equipment. In some cases, however, an insulation failure may result only in a short-circuit between turns, for example, in a motor shunt field coil. The result would be an increase in current in the circuit, which may or may not be sufficient to cause further insulation breakdown by excessive heating, according to the amount of the winding short-circuited. The short-circuiting of a turn or turns in a transformer winding is practically certain to result in a burn-out due to the current induced in the short-circuited turn by the magnetic flux. Short-circuited armature coils cause undue heating and sparking at the commutator. Faults in machinery are, however, sometimes elusive, owing either to their high resistance, their appearance only at certain speeds, or other factors. In order to guard against the operation of faulty plant, the insulation resistance of individual units should be tested periodically and the results logged. On the occurrence of an abnormal test the cause should be sought without delay, and the incipient fault removed. To localise faults in machines it may be necessary to disconnect leads piecemeal; care

should obviously be taken to check reconnections, especially the shunt and other field windings. Very high resistance faults may require breaking down before they can be localised. This may be best accomplished by the application of 2 000 V or more D.C., obtained by valve rectification (§ 481) if the apparatus is inductive, but the current that can be passed through the fault should be limited to a few amperes in order to avoid unnecessary extension of the damage.

Short-circuited turns and even faults due to short-circuiting by carbon dust, etc., can be treated by a 'Ducter' testing set (Vol. 1, 5th edn.), which is an ohmmeter for measuring resistances from a few ohms down to 1 microhm. Such sets are commonly used in electric railway and tramway shops.

1027. Cable Testing, Before and After Laying.—The properties of rubber, textile materials and paper have been considered in Chap. 2 and § 287, Vol. 1. Rubber is little used as an insulator except for relatively small cables and wiring, and for short connections between machines, instruments, etc. Textile and similar materials are largely employed as indicated by their qualities (§ 74) in the insulation of conductors in machines. Paper, impregnated with compound, is almost exclusively used for the insulation of high-tension cables, the testing of which is now considered.

The conductors of cables are seldom tested for their ohmic resistance after manufacture, except as a preliminary step in the location of insulation faults (*q.v.*); their conductor sizes are standardised with small tolerances (*see* B.S.S. No. 7) and their scheduled resistances can be assumed correct for all ordinary purposes. It is necessary, however, to take into account the influence of temperature in any conductor test (§ 61). Tests before delivery are chiefly designed to ensure satisfactory insulation. For this purpose, bending, voltage, and insulation resistance tests are applied.

B.S.S. No. 7 specifies, *inter alia*, that a bending test shall be applied to a sample of a length 60 times its overall diameter. The sample shall be bent around a barrel whose diameter is 12 times the cable diameter, first in one direction and then in the other three times, making 6 bends in all, after which the sample must withstand its appropriate voltage test. For the latter a length of cable shall be immersed in water for not less than 24 hrs., and then have applied to it, between conductors and between conductors and earth, an alternating voltage of approximately sine-wave form at any frequency between 25 and 100 cycles per sec.; this voltage shall be applied gradually and maintained constant for 15 mins. The testing voltages to be applied are shown in Table 219.

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TABLE 219.—*Test Voltages for Cables at Works and When Laid and Jointed.* (See also B.S.S. No. 7.)

Working Voltage.	Type of Insulation.	Testing Voltage at Works.	Testing Voltage Laid and Jointed.
250	Vulcanised India-rubber . . .	1 000	500
660	Jute, Jute and V. Bitumen . . .	1 500	1 000
660	Paper, V.I.R., V.B., Paper and V.B.	2 500	1 000
2 200	" " " " "	6 000	4 000
3 300	" " " " "	10 000	6 000
5 500	" " " " "	15 000	10 000
6 600	" " " " "	18 000	12 000
11 000	" " " " "	25 000	20 000

For systems of 2 200 V and higher the testing voltages between conductors and earth are diminished to 60 % of the values shown in Table 219 if the neutral is earthed. For concentric systems with the outer normally earthed, a testing voltage of 2 500 V at works (1 000 V laid) is to be applied between outer and earth, irrespective of the working voltage of the system.

1028. High Voltage Cable Tests.—In extra-high-tension work the high voltage test may be either A.C. or D.C. During manufacture it is applied to individual drum lengths or to a few drums only at a time, so that the capacitance is not very high and A.C. may be conveniently used without necessitating a large transformer. When laid, however, it may be desired to test several miles of cable at once and a transformer of several hundred kVA rating might be required to supply the leading wattless current taken by the capacitance. Hence D.C. testing is frequently adopted, although the ratio of D.C. voltage to A.C. crest value varies somewhat for different insulators and at different temperatures. Experience appears to show that D.C. of a given voltage may, in the case of buried cables, be almost twice as severe a test as the corresponding A.C. crest voltage. Several means are possible to produce high-voltage D.C., *e.g.* a number of small dynamos in series, the mechanical rectification of A.C., and thermionic valve rectifiers. Because of their relatively small bulk and simple operation valve rectifiers are now usually employed, several forms being available (§ 419, Vol. 2).

Great caution is necessary in pressure testing, particularly with extra-high-tension. Everything that may be touched must be solidly earthed. After a core has had voltage applied to it, it must be earthed for several minutes before it can be considered dead. All temporary wiring should be mechanically strong whether the

current is large or small, and so connected that alterations and final earthing are done by proper switches with adequately insulated handles or by isolators through a wood or other properly insulated switch-stick.

1029. Cable Insulation Resistance.—The insulation resistance of cables is frequently measured at manufacturers' works by means of a direct-reading galvanometer (§ 96, Vol. 1), but when laid most usually by a portable ohmmeter (§ 119). In the former case the charging current taken by a cable causes the galvanometer pointer to swing far beyond the reading at which it finally settles, and in fact the leakage current does not become quite constant for a matter of hours. By arbitrary custom, however, the reading of the galvanometer after an electrification of one minute is taken to indicate the leakage current.

1030. Cable Power Factors.—Such insulation tests as are mentioned in the preceding paragraph become impracticable at high voltages and, moreover, yield data which are found in practice to give little information as to the quality and probable length of life of the insulation. There is, at the time of writing, no perfectly acceptable method yet available which, by means of a short time test, provides a basis for the logical predetermination of the behaviour of cables for voltages above about 33 kV, although much research is being devoted to this matter. The effects of voids in layered insulation are known to be prejudicial (§ 79, Vol. 1) and manufacturers endeavour to avoid them. The ideal insulation for any cable would partake of the nature of an air condenser; its charging current would lead on the voltage by exactly 90° and there would be no component in phase with the voltage. In other words, the power factor of the *charging current* would be zero. Any component in phase with the voltage must cause wattage dissipation in the insulation (hence heating) and tend towards degradation of the insulation; thus a measurement of the power factor of the charging current of a cable gives some information of value in the estimation of quality. If, moreover, the power factor is found to remain sensibly constant after several cycles of heating and cooling, such as are experienced in the commercial working of a cable owing to variable loading, it is a fair inference that the insulation is stable and likely to have a long useful life. Hence the testing of extra-high-tension cables is mostly directed to the accurate measurement of the power factor of the leakage current through the insulation.

Instead of measuring the cosine of the angle of lead, actual measurements give results in terms of the tangent of the angle by which the leakage current departs from its ideal 90° lead. Since this angle is very small the measured quantity is closely approximate to the former value, and indeed the voltage multiplied by the current and the 'power factor' so found can be taken as equivalent to the watts dissipated in the insulation. One method of measuring the power factor consists of a wattmeter reading, but the Schering bridge method is generally considered more accurate and convenient. The difficulty with a wattmeter is that the multiplying resistance in circuit with the voltage coil of the instrument (§ 109, Vol. 1) necessarily introduces a capacity to earth for which it is difficult to compensate or otherwise make allowance for in testing. The nearest approach would be to shield each section of the resistance, maintaining the shields at

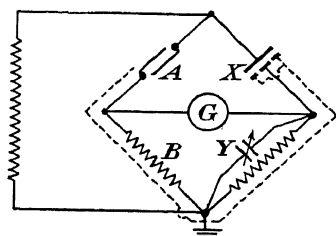


FIG. 417.—Simplified diagram of usual form of Schering bridge.

appropriate voltages to earth, and this is obviously not easy to arrange without excessive bulk and complication; various methods have been proposed and adopted (see Bibliography, § 1038).

The Schering bridge is made in several forms; in one very convenient pattern, when balance is obtained, the power factor of

the condenser (or cable) under test is read direct. There are four arms, as indicated in Fig. 417. The insulation of cable *A*, in series with a variable ohmic resistance *B*, is in parallel with a standard air condenser *X* in series with a fixed ohmic resistance *Y*, and the latter has a variable condenser in parallel with it. The galvanometer *G* is of the vibration type (§ 96, Vol. 1), consisting of a moving iron, carrying a mirror and suspended between the poles of an electro-magnet having two windings. One winding takes the out-of-balance current (A.C.) of the bridge, while the other is traversed by a direct current, the value of which controls the period of vibration of the moving iron instead of varying the tension of the suspension for that purpose. When the bridge is balanced there will be no A.C., and the spot of light reflected from the galvanometer mirror will cease to vibrate. If the values of the arms *B* and *X* are fixed, it follows that when balance is obtained

the power factor of the branch Y will measure that of A . The power factor of branch $Y = 2 fRC$, where R is in ohms and C in farads. If C is calibrated in microfarads and the standard frequency is 50 the reading will be 1:10, if the value of R is fixed at $1000/\pi = 318.4$ ohms. In order to avoid the effects of capacity currents due to the capacitance of the bridge connections, all of the latter are guarded by earthed shields, as indicated by the dotted lines in Fig. 417. Frequently other refinements and methods of compensating for capacity and leakage currents are introduced in practical working.

Such a bridge is suitable for measuring the power factor of the insulation currents of cables on drums or otherwise having their sheaths insulated from earth. In the case of laid cables it is essential to arrange the earth connection direct to the cable sheath. The arrangement shown in Fig. 418 has proved useful, but it is necessary to take two measurements. The first is made without the core of the cable connected to the bridge, and takes into account the leakage paths and capacitances existing apart from the cable insulation. The second measurement, with the core connected, gives an overall figure from which the true power factor of the cable alone can be calculated.

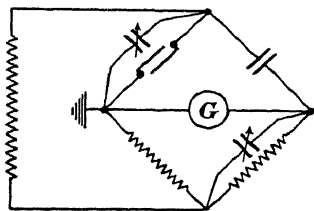


FIG. 418.—Modified arrangement of Schering bridge, for use in measuring the power factor of insulation currents of laid cables.

1031. Testing Live L.P. Systems.—The effects of leakage currents from low-pressure systems are not so immediately disastrous as when high voltages are in question, and moreover it is commercially practicable to provide a higher factor of safety in the insulation. Low voltage cables and cable networks can be tested by direct-reading ohmmeters (§ 119, Vol. 1) and similar instruments, when disconnected from the source of supply, and fairly reliable tests may also be taken on a complete system while alive. In the simplest case of an unearthed two-wire D.C. system, let the insulation resistances of each main be represented by resistances R_1 and R_2 respectively. Connect R_3 (Fig. 419), which may be the resistance of a voltmeter or a relatively low resistance, according to conditions, in parallel with R_1 and observe the voltage across it = V_1 . Then the current passing through R_1 and R_3 in parallel

must be equal to that passing through R_2 . The combined resistance of R_1 and R_3 is $R_1 R_3 / (R_1 + R_3)$ and, by Ohm's Law, the current is therefore $V_1 / (R_1 R_3 / R_1 + R_3)$. The same current flowing through R_3 may also be written $E - V_1 / R_2$. Thus

$$V_1 R_1 R_2 + V_1 R_2 R_3 = E R_1 R_3 - V_1 R_1 R_3. \quad (1)$$

Similarly, after connecting R_3 in parallel with R_2 and measuring the voltage V_2 across it, we obtain

$$V_2 R_1 R_2 + V_2 R_1 R_3 = E R_2 R_3 - V_2 R_2 R_3. \quad (2)$$

Thence

$$V_2 R_1 = V_1 R_2,$$

$$R_1 = R_2 \frac{V_1}{V_2}. \quad (3)$$

Substituting (3) in (2),

$$R_3 = \frac{R_2 [E - (V_1 + V_2)]}{V_1}$$

and

$$R_1 = \frac{R_3 [E - (V_1 + V_2)]}{V_2}.$$

Similar expressions may be obtained for 3-wire systems.

An approximate method of ascertaining the insulation resistance of the neutral conductor of a 3-wire system is to apply an artificial

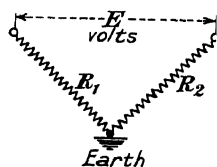


FIG. 419.—Equivalent resistance of leakage paths to earth and artificial leak resistance.

earth leak of x amperes to one outer and observe that y amperes return through the neutral earthing resistance. Since the return current splits inversely as the resistance of the available paths, if R is the resistance of the earthing resistance, the insulation resistance of the neutral conductor = $R[y / (x - y)]$. If this

resistance is low there may be more than one fault in the insulation.

In any large system there generally exist several relatively high resistance faults simultaneously, and these tests taken while alive are not very helpful to localise such faults. It is preferable, therefore, to arrange to isolate every part of a network periodically and to test such parts while dead. This routine procedure is facilitated by the liberal use of sectionalising points, by which means it is possible to avoid interrupting the supply to consumers.

As a rough continuous indication of the state of the mains, use may be made of the principles explained in § 472, Vol. 2. On a 2-wire system two lamps are joined in series and connected between

the poles of the circuit in the power-house, the connecting wire *between* the lamps being earthed; *each* lamp should be rated for the full voltage of the supply. If then the insulation of the two wires is equal, both lamps will glow equally red-hot; if one lamp is brighter than the other, the pole to which it is connected has a higher insulation resistance than the other; and if one lamp is out, and the other at full brightness, there is a bad "earth" on the former pole. In either case, if both wires are equally faulty there is no indication given.

1032. Cable Fault Localisation.—Localisation of cable faults can be very accurately carried out in favourable circumstances. The type of test required depends on the type of fault, and this must be ascertained before localisation can be attempted. In high-tension cable work a fault often makes its location clearly evident by the mechanical damage due to the large amount of energy fed into it, but with modern high speed discriminating protective devices in use (Chap. 15, Vol. 1) this is not always so, the faulty section being isolated before the fault has fully developed. Some indication of the location of a fault in low-tension cable networks where the cables are in conduits can often be obtained by the characteristic smell in the manholes.

In general, cable faults can be divided into (*a*) core to earth breakdowns, (*b*) core to core short-circuits, and (*c*) open circuits. The former are the most common and frequently develop into the second type. Open circuits are rare, except in districts liable to subsidences. All types of cable faults are most easily localised and their effects minimised in closely sectionalised networks protected by carefully graded fuses or circuit-breakers.

Core to earth breakdowns can be roughly localised by fall of potential tests, but these are not recommended on account of the difficulty of obtaining steady conditions. They consist of passing a current through the faulty cable to earth, using the distant part of the cable and a sound cable as a voltmeter lead to determine the drop in voltage between the near end and the fault. Knowing the current and the drop, the resistance can be calculated, and thence the distance of the fault from the known size of the cable and its resistance per yard.

Loop tests of many varieties have been devised to locate cable faults. The principle loop tests are known as the Murray and Varley, the former being more suitable for low resistance mains, *i.e.* large cables. All loop tests are special applications of the Wheatstone Bridge (§ 120, Vol 1). In order to eliminate variables it is essential to arrange that the fault is in the battery circuit.

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Murray Loop.—The faulty cable is looped with a sound one at the far end and the combined resistance $b + x = R$ is first determined, by any bridge or other method. Connect as in Fig. 420; the notation in this diagram is the same as that in Fig. 26 (§ 120). The arms a and b are then adjusted until balance is obtained. Then $x = r \times b / a$ but $b = R - x$, hence $x = Rr / (r + a)$. Thus the 'distance' of the fault in ohms is obtained.

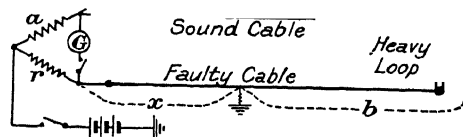


FIG. 420.—Diagram of Murray loop test.

Varley Loop.—This (Fig. 421) is similar to the Murray loop, with the addition of a resistance y . Again $x = r \times b / a$, but $b = R - (x - y)$ hence $x = r \times (R - x + y) / a = r(R + y) / r + a$. Thus the 'distance' of the fault, $x - y$ ohms, can be obtained. If the ratio arms a and r are equal, the fault distance is $R + y / 2$ ohms.

Portable instruments for conveniently carrying out these tests are available in various forms. Fig. 422 shows the Bridge Megger

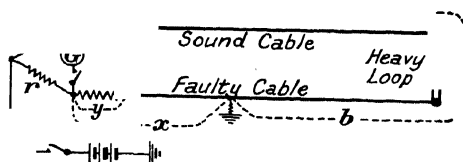


FIG. 421.—Diagram of Varley loop test.

connected up for a Varley loop test on a three-core cable, one core of which has an earth. If L is the total resistance of the loop and R the resistance required in the resistance box to obtain balance on the galvanometer, then D , the distance of the fault in ohms, is $(L - R) / 2$.

It is necessary to arrange that the loops at the far end shall be of negligible resistance, as well as the connections to the bridge resistances; any allowance for such leads in the foregoing tests involves simple subtraction from observed resistance only. In the method of localisation giving results as a percentage of the total length of the conductor it is necessary to convert any allowance for leads into an equivalent length of conductor of the cable section. If the whole of the cable

concerned in such tests is not of the same section, the section of one length must be taken as standard and the lengths of the remainder converted into the equivalent length of that section.

The slide wire equipment for localising faults substitutes a length of wire that can be tapped at any point for the arms

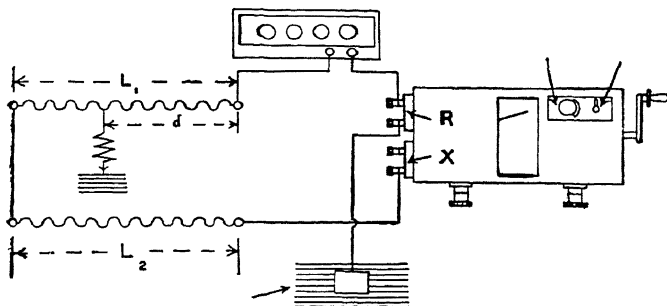


FIG. 422.—Connection of 'Bridge-Megger' for fault location by Varley loop test. (Courtesy of Evershed & Vignoles, Ltd.)

a and b in a Murray loop test. The position of the battery tapping is varied until no deflection is shown on the galvanometer, in which

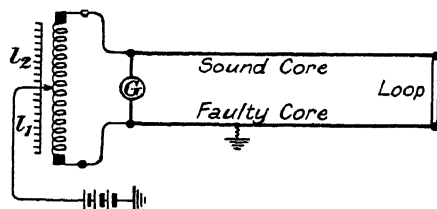


FIG. 423.—Slide wire test connections.

condition the ratio of the amount of wire on either side of the tapping is the same as the ratio on the cable resistance on either side

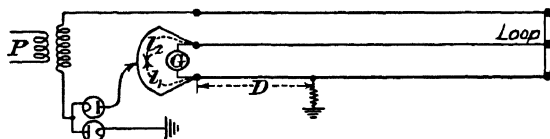


FIG. 424.—High voltage slide wire test for high resistance earth.

of the loop up to the fault. Fig. 423 shows the connections of a low voltage testing set in which the wire is mounted on a cylinder which can be rotated. Fig. 424 shows the same principle applied

in a high-voltage testing equipment for the location of a high resistance earth; the distance D is given by $Ll_1 / (l_1 + l_2)$.

In cases in which no sound core is available with which to form a loop (as when the fault involves all three cores of a cable) the use of pilot or telephone cables is practicable, or a special lead may be run temporarily for the purpose.

It is difficult to obtain reasonable accuracy with the Varley loop test unless the resistance of the loop is at least 1 ohm; this test should therefore not be used with low resistance cables.

Localisation of open circuits is more difficult on low-tension than on high-tension mains because the only practicable methods involve the capacitance of the insulation of the cable and this is generally less perfect in the first case; also it may not be permissible to use a very high charging voltage on low-tension gear and hence the amplitude of the testing current will be relatively low, tending towards small and unreliable instrument readings. A normal test requires only a changing battery, a change-over discharge key and a galvanometer. Using great care to avoid promiscuous leakages, the cable core which is broken is charged from one end to a given voltage and then discharged to earth through the galvanometer. This is repeated from the other end, noting the deflections in each case. The position of the fault is determined by the ratio of these readings. Alternatively, if similar cores are available, one being open-circuited at a fault, the capacitance of a sound core can be compared with that of the core which is broken. Another method consists in determining the actual capacitance from each end by comparison with a variable condenser. All of these tests are applicable only to cable which is of the same conductor size and has uniform thickness and type of insulation throughout its length.

Inductive Localisation.—A different method of fault localisation on low-tension cables, using an inductive coupling to a telephone circuit, has been employed with success in some cases. In A.C. systems a small current, restricted by a suitable resistance or choke, is allowed to flow along the damaged cable and back through the fault and earth. An exploring coil (say 250 turns on a triangular frame of 3-ft. sides) in series with a telephone receiver is then passed along the route of the cable, the hum due to the fault current being heard in the receiver until the fault is reached. Theoretically, the sound should cease beyond that point, but in

practice the fault current does not wholly return by the cable sheath and armouring, and the stray current may affect the telephone beyond the fault. Usually, however, there is a sufficiently distinct variation of the received signal in the region of the fault to locate it within a short distance. On a D.C. system some type of interruptor is necessary in the feed to the faulty cable to enable the telephone to pick out the variation in flux due to the current passing; a thermal or other 'flicker' interruptor as used in certain lighting display signs can be utilised for this purpose. The method is not easily applied to A.C. mains where the faulty cable follows the same route as other cables which must remain alive, nor can good results be expected where the cable is heavily armoured and deeply buried. A somewhat similar method can be used, however, to identify cables, healthy or otherwise, whether armoured or not. The marking current is similarly applied, but interrupted by clockwork or similar means for a fraction of a second or two. The telephone search coil is compressed into a smaller size so that it can be brought close to the cable in a trench or manhole, and an amplifier may be necessary. A cable carrying normal current will induce a continuous hum in the telephone circuit, whereas the cable carrying the marking current will be identifiable by the superimposed periodic interruptions in the hum.

1033. Testing Ceramic Insulators.—Porcelain, glass, and steatite are employed for insulating purposes at all voltages (Chap. 2, Vol. 1). It is impracticable to test individual insulators of this kind for insulation resistance on the same lines as a cable, and the tests applied are designed to discover the ultimate break-down values, electrical and mechanical, of a type, and subsequently to ensure that individual insulators do not depart seriously from the typical values. ✓For extra-high voltage insulators it is now usual to employ routine tests with normal and high frequencies; and insulators are also subjected to impulse surges in type tests. The necessary high voltages are obtained, as regards normal frequencies, by transformers similar to the ordinary power type, but usually single-phase and with specially designed windings and insulation. By means of series (cascade) connections, Fig. 425, in which the cases of the second and subsequent transformers are insulated from earth and maintained at a definite voltage relation with their windings, very high voltages may be obtained, reaching 1 000 kV or higher crest

value. The transformer connections are brought out through bushing terminals (§ 368, Vol. 1) and considerable space is required to give the necessary clearances. The voltage obtained is measured by (a) ratio calculations, and (b) sparking distances between spheres (§ 105). Such sphere gaps are often made adjustable by remote control, but this is not essential for routine tests where a definite voltage can be arranged and indicated on a suitably calibrated instrument connected to the primary circuit. A hundred or more similar insulators are arranged in a batch on a conductive table, and a small chain makes contact with each from a suspended H.T. framework, so that all are tested simultaneously in parallel; the character of

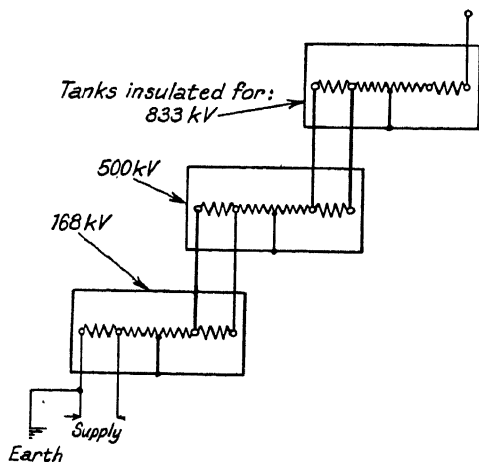


FIG. 425.—Cascade arrangement of transformers for 1 000 kV. (Courtesy of Ferranti Ltd.)

the discharge is entirely changed if one insulator breaks down, and the faulty one is readily observed. For this typical routine test, and indeed all high-tension testing, the whole of the gear other than the insulated control apparatus is protected by rails and guards, the doors in which are interlocked with the control switches, so that voltage cannot be applied with the gear accessible. ✓

High frequency, high voltage tests are employed, *inter alia*, to detect air voids in compound-filled porcelain bushes. They are applied generally by means of an air-core Tesla transformer, the primary of which is fed from a normal frequency circuit through a condenser, an arc-gap being coupled in parallel across the mains. ✓ At a certain point in each voltage rise an arc starts across the gap, forming a discharge path for the condenser; thus the circuit composed of the primary winding and the condenser is set oscillating at high frequency. The secondary of the transformer is 'tuned' to the primary by a parallel condenser, and raises the voltage of

the high frequency oscillations. In order to cool the arc electrodes an air blast is usually employed.

Impulse surges, imitating the steep-fronted transients due to lightning, are usually generated by means of the Marx multiplying circuit, a simplified diagram of which is given in Fig. 426. The number of steps can be arranged as required to give the desired surge amplitude, in relation to the initial voltage necessary to charge the condensers CC . As shown, the diagram indicates valve rectifiers, but mechanical Delon-type rectifiers may be employed. The

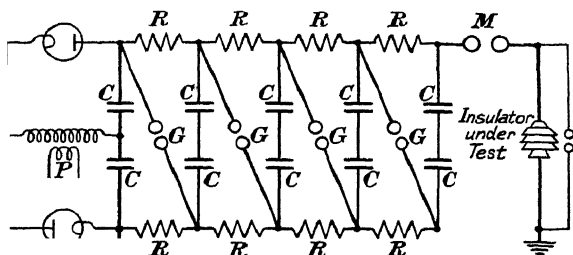


FIG. 426.—Simplified Marx surge generator circuit.

condensers are thus charged in parallel through the resistances RR , which are of the order of a megohm each. At their full voltage they break down the gaps GG , and discharge in series through them and the measuring gap M . Some part of the discharge passes through the charging resistances, this being the reason why they are made of a high value. High frequency voltages and surge impulses are utilised in testing other apparatus besides ceramic insulators, such as lightning protective gear and so forth.

According to B.S.S. No. 137 (1930), porcelain insulators are to be tested with a voltage the crest value of which does not exceed 1.45 times its R.M.S. value; this is commonly specified for most high voltage tests. The specified voltage must be sustained for 1 min. by a dry insulator, and then it is raised to determine the dry spark-over voltage. With the top and tie groove covered with lead foil and the insulator immersed in oil a specified 'puncture' voltage must be sustained for a period only long enough to read the voltage, the latter being only carried up to an actual puncture in type tests; suspension units are to be submitted to 1.3 times the dry spark-over test voltage. Specified voltages must be reached in a 30-sec. rain test and as a wet spark-over. The water used is to have a volume-resistivity of 9 000-11 000 ohm-cms., to be within 10° C. of the ambient temperature, and be applied at 45° to the vertical at a rate equivalent to 0.2 in. rainfall per min. The spray is to be in operation for 2 mins., with half the test volts applied, before the voltage is raised to that specified. A temperature cycle test comprises three repetitions of being heated in water at 70° C. for 1 hr., then immediately immersed in ice and water not above 7° C. for 1 hr.; the cycle to be followed by a routine high voltage

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test. Suspension and tension insulators are to be submitted to electro-mechanical tests comprising an axial tension of $2\frac{1}{2}$ times the maximum working load for 1 min., with the simultaneous application of 75 % of the actual dry-spark-over test volts. For the routine high voltage test, a pin insulator is inverted and immersed in water to cover the testing terminal and any clamp or binder attached to the neck groove; the spindle hole is filled with water and a voltage applied which just causes sparking over. This voltage must be sustained for 5 mins. without puncturing the insulator, ✓

1034. Testing Transformer and Switch Oil.—The insulating properties of oil have been discussed in § 77, Vol. 1. In order that satisfactory service may be given by oil-immersed apparatus it is essential that the oil shall be in good condition, and tests to determine its state are necessary not only for suppliers but also for users. Oil testing requires care and some experience, otherwise reliable results are not obtained. For this reason B.S.S. No. 148 (1927) not only prescribes the values required but also the method of testing in each case. It adopts the Michie test for the tendency to sludge; explains how to determine the loss by evaporation, the flash-point and viscosity of an oil; prescribes a cold test, the method of testing the dielectric strength, the acid and saponification values and the tendency to copper discoloration. Specific gravity is not specified, since it does not appreciably affect the suitability of oil for transformer and switch use; the quotation of specific gravity, in conjunction with the other qualities, is, however, useful as giving some indication of the source of the oil.

B.S.S. 148 recognises two classes of oil: *Class A oils* are suitable for use in transformers working at temperatures above 80° C.; while *Class B oils* are for transformers whose temperatures do not usually exceed 75° C. The Michie test for sludging comprises the maintenance of 100 grm. of oil at 150° C. for 45 hrs. in a flask fitted with a reflux condenser. Purified air is passed through the oil at the rate of 2 litres per hr., and a piece of copper foil is present in the flask. The resulting oxidised oil is diluted with petrol and allowed to stand for about 24 hrs. An oil is classed A or B according to whether the brown deposit (sludge) thus caused is less than 0.1 or 0.8 % respectively. In America a 'life' test is preferred, samples of oil being heated at 120° C. in a rotating apparatus with a slow stream of air passing over them; the 'life' is taken as the number of days before sludging begins. The German tar-value test consists in maintaining the sample at 120° C. for 70 hrs., whilst oxygen is passing through it, and then measuring, by chemical means, the degree of acidity developed. In neither the 'life' nor 'tar-value' tests is copper present. The Brown-Boveri test maintains oil at 112° C. for 300 hrs. in the presence of copper, air and cotton, taking note of the amount of sludge and acidity produced and the decrease in tensile strength of the cotton. Other factors, including the presence of iron and electrostatic stress, are added in the tests advocated by the Swedish General Electric Company. This test comprises the maintenance of the oil sample at 100° C. for 100 hrs., with an oxygen stream through it, in the presence of concentric cylinders of iron and copper held at 10 kV per cm. apart; other tests

are specified in order to obtain a measure of the rate of sludge formation as well as its total amount.

Flash-point in the B.S.S. is measured by a Pensky-Martin apparatus and viscosity by Redwood viscometer. The cold test is to ensure that an oil is fluid at a specified temperature, and a definite procedure is laid down; similarly, proof that the oil contains neither organic or inorganic acids, nor sulphur, is also required. All the foregoing tests apply chiefly to new oil supplies, but the dielectric strength test is of more general application; it should be employed periodically and after centrifuging or filtering to ensure that the oil has not deteriorated. The chief source of trouble with insulating oil is the presence of moisture, a small trace of which lowers the dielectric strength greatly; fibrous material in the oil also affects this condition. According to the B.S.S., the test is taken by observing the voltage at which a sample breaks down, the voltage being applied between two 13 mm. spheres 0.4 mm. apart, immersed in the oil contained in a case $100 \times 55 \times 90$ mm., with the tops of the spheres 50 mm. below the top of the case. The initial voltage is 10 kV, raised rapidly to 30 kV for 1 min. without causing break-down. Newly centrifuged oil sometimes withstands 70 kV.

The oil used to impregnate paper insulation on cables is not tested apart from the paper except by manufacturers. Jointing compound for cable boxes is also seldom tested, although its dielectric strength with a given thickness and temperature gives some indication of its quality; its percentage shrinkage on cooling is commonly quoted. The dielectric strength of these materials can readily be ascertained with the same apparatus as that used for switch and transformer oils. Bitumen for solid filling is chiefly employed as a mechanical protection and its bulk is therefore important; as it is purchased by weight its relative value varies inversely with its specific gravity.

1035. Meter Testing.—Ordinary A.C. integrating meters (§ 115, Vol. 1) measure the product of true watts and time, automatically compensating for power factor. On D.C., ampere-hour meters are largely used, calibrated to read directly in kWh at a standard voltage (§ 114). The principal tests in every case are for (a) starting load, and (b) accuracy at various loads (and power factors, in the case of A.C.). In addition, tests may be taken of the watts consumed by shunt coils, and of the voltage drop across series coils; these are quite straightforward, but should be taken after the coils have attained steady working temperatures.

Except for large and important A.C. meters, which may be tested singly, tests are generally carried out on batches of similarly rated meters. In order to avoid dissipating energy unnecessarily the current coils are coupled in series and supplied at low voltage, while the shunt coils are coupled all in parallel and supplied at

normal voltage. In the case of single-phase meters the series coils will have very small reactance and the current in their circuit will be practically in phase with the voltage; the reactance of the shunt coils will be high and the current in them will therefore lag by approximately 90° . The exact quadrature relation between the fluxes due to these two currents is a necessary condition for the accurate measurement of inductive loads by single-phase meters; it may be checked by connecting the coils to the phases of a 2-phase system, in which case no torque should result, *i.e.* the meter should not start.

A supply for the current coils is usually obtained from a special transformer, wound to give up to about 10 V and currents up to the maximum required for the testing work to be undertaken. An ordinary current transformer reversed should not be employed, on account of wave form distortion. Energy for the shunt coils may be taken from another transformer, generally with many tapplings to cover a wide range of voltages. Instead of the two transformers, or behind them, two small alternators may be employed, direct-coupled to the same motor and with the frame of one alternator mounted so as to be movable through a certain angle. By this means a controllable phase difference can readily be produced between the current and voltage supplies, thus facilitating tests at other than unity power factor. Meters for use on different frequencies can be tested on their rated periodicities if the driving motor is of the variable speed type. Care should be taken to specify and ascertain that the alternators have voltage wave forms very closely approximating to the correct sinusoidal shape.

If a phase-setting generator set be not available, tests at other than unity power factor can be undertaken by the insertion of a choking coil or other reactance in the current circuit, or, better, by the use of a transformer with a movable secondary, on the lines of an induction regulator (§ 142), employed to supply the shunt coils with a voltage having any required phase relationship with that to the current coils. When a 3-phase 4-wire system is available, two transformers coupled to the different phases on the primary side may have their secondaries, or tapped portions of their secondaries, in series, so as to obtain the desired phase shift, or a potentiometer-like connection of resistances may be made across the phases, with a movable tapping point. The power factor is, in any case, calculated from the readings of standard voltmeters, ammeters, and wattmeters.

Accuracy tests depend for their validity upon the quality of the instruments used as standards. These are chiefly dynamometer wattmeters of special construction,* with their calibration curves known accurately by virtue of a certificate issued usually by the National Physical Laboratory. When it is necessary to use current or potential transformers with such instruments their calibration curves must also be known.

When a batch of meters has been hung on the testing bench and wired up to the voltage and current terminals the shunt circuits and full load in the current circuits are switched on. Strictly, no testing should proceed until a steady temperature is reached, but in commercial testing it is usual to wait only until the shunts are fully warmed up. Similarly, after overload tests the meters should be allowed to regain normal temperatures before any further tests are taken.

The minimum running current of each meter is then ascertained and the time taken to make three revolutions checked. The current should not exceed 0.5 % of rated full load, and care must be taken to eliminate vibration. An over-voltage of 10 % without current should not cause starting; with clock-type meters a run of several hours is necessary to ensure that this requirement is met. The loading of the batch is then set (usually $\frac{1}{10}$, $\frac{1}{4}$, $\frac{1}{2}$, or full rating) by reference to the wattmeter and by adjustment of a series resistance or of the generator field rheostat. Careful observation is made to ensure that the load remains quite steady during testing. Each meter is then observed in turn, a number of complete revolutions being timed by stopwatch. No reference is made to the index readings, but the correctness of the train of wheels should be checked at some time before or after the load test.

The makers furnish each meter with a 'testing constant,' generally given as revolutions per kWh, but sometimes as watt-hours, watt-minutes, or watt-seconds per revolution. In the first case, if K is the maker's constant and K_0 the observed constant, obtained from a stopwatch-load test, the percentage error of the meter may be taken as $100 (K - K_0) / K$. If, however, the constant is given in the form watt-hours per revolution the percentage error is usually taken as $100 (K - K_0) / K_0$. The percentage method of expressing the error is not ideal, however, and some engineers prefer to develop

* See, for example, illustration facing p. 152, Vol. 1.

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their own constant, which is the factor by which the meter reading must be multiplied in order to bring its indication to the correct value.

B.S.S. No. 37—1930 provides, *inter alia*, that the error shall be expressed as a percentage of the true kWh. If R is the registration and kWh the true units the percentage error is $100 (R - kWh) / kWh$. If T is the true time for correct meter and t the actual time observed for a given number of revolutions the percentage error is $100 (T - t) / t$.

Other requirements of this specification are that over-voltage up to 10 % for A.C. (5 % for D.C.) at loads between $\frac{1}{10}$ and full must not change the rate of registration more than 1 %. On D.C. the change of voltage should be gradual and the voltage circuit not broken. For commercial grade meters a variation of frequency 5 % up or down must not affect registration more than 0.5 % at unity power factor or 1.5 % at 0.5 power factor. These tolerances are respectively 0.25 % and 0.5 % for a similar variation of frequency.

Three-phase meters of the two-element type may be tested one element at a time, but both voltage coils must be excited during each test. There are many possibilities of wrong connections. To check the accuracy of the connections, provide a unity power factor load and then open either the voltage or current circuits of each element in turn; the elements remaining in action should drive in the same direction in each case. Alternatively, using any balanced load, the meter will stop if the voltage coil connections of the two elements be interchanged.

Routine tests of large numbers of similar motor meters are sometimes undertaken by stroboscopic observation of the disc of each meter simultaneously with that of a rotating standard. By means of suitable arrangements of mirrors it is possible to observe any differences of speeds very quickly, and even to estimate whether in given conditions the difference is within permissible limits, without any calculations or stopwatch timing. Practically all A.C. meters are now of the induction type, and these are much less affected by stray fields than was the dynamometer type previously in common use. Nevertheless, it should be specified that the accuracy of registration shall be unimpaired by stray fields, and the stroboscopic method forms a convenient means of rapid checking, since it can be carried out readily with the meter to be tested mounted in any predetermined stationary or moving flux.

Meters to be operated in conjunction with current and potential transformers may be either tested complete with these components or separately. The former is preferable, but it involves testing equipment of much greater range than the latter method, which

necessitates merely the superimposition of the calibration curves of the three pieces of apparatus. A potential transformer may be tested for ratio by opposing it by a standard and measuring the difference. Its phase angle measurement is more difficult, but it may be determined by opposing its voltage with a voltage across a non-inductive resistance potentiometer in series with a calibrated galvanometer, setting the latter to give zero on a vibrating galvanometer. The errors of potential transformers are usually quite appreciable, as they may easily amount to 1 % as regards ratio error and to $\frac{1}{2}^\circ$ or more as regards phase error, depending chiefly on the size of the transformer and the nature of the secondary burden. They are, however, constant over the entire current range of the meter with which the transformer operates. On the other hand, although the ratio and phase angle errors of current transformers are reasonably small at their rated burden they vary continuously throughout the range of the meter loading. Tests on current transformers for ratio and phase errors may be carried out by comparing the transformer under test with a standard transformer using a form of differential wattmeter with an auxiliary supply, capable of phase adjustment, to the pressure circuits. More absolute methods involve the use of non-inductive shunts in the primary and secondary circuits, the voltage across the shunts being equated by means of adjustable resistances and condensers or inductances until a zero reading is obtained on a vibration galvanometer.

The testing of D.C. integrating wattmeters follows similar lines to that of A.C. meters, and, indeed, the same standard wattmeters can generally be used. For ordinary D.C. service purposes, however, ampere-hour meters are principally used and thus a standard ammeter is required instead of a wattmeter; Kelvin ampere balances are still used in some cases for such work and are capable of very accurate results.

Electrolytic and clock-type meters can only be tested by prolonged load runs. It is preferable to arrange a batch of such meters in series with one of another type whose accuracy is known, rather than to attempt to control the constancy of the load for the whole period of a long run.

1036. Testing Fans.—The efficiency of large fans, such as those used for mine ventilation, can be ascertained by comparing the electrical input to the motor with the power theoretically

required to move the amount of air against the head due to the resistance of the air circuit. For given conditions, an 'equivalent orifice' can be calculated, and the fan may be tested delivering through an actual orifice, the characteristics of which are known. The determination of the efficiency of such a fan when erected in its normal operating conditions is not an easy task, however; it involves the measuring of both the static and velocity head produced by the fan and the quantity of air moved. From these data, the power in the air can be calculated and thus the efficiency obtained. (*See also* §§ 763-765.)

Methods of specifying the performance of industrial fans have been largely standardised as a result of the work of a Committee of the Institution of Heating and Ventilating Engineers appointed in 1927. Smaller fans, such as ceiling and desk types, present peculiar difficulties, since they are used without clearly defined inlet and outlet channels. Their performance is specified in B.S.S. 367—1929 and 380—1930. In these specifications all attempts to arrive at a true efficiency figure (*i.e.* the ratio of power in air to motor input) have been abandoned; performance is specified in terms of the number of cubic feet moved per minute per watt input, this figure being called the 'Service Value.'*

B.S.S. 367 relates to ceiling fans, *i.e.* those of large diameter, medium-speed propeller type, and is limited to fans with blade diameters between 48 and 60 ins. Investigations showed that with a fan of this type suspended above a four-sided screen the flow of air is characteristic; it consists of a central stream of relatively high-speed air, only slightly larger in diameter than the blade sweep, and a surrounding induced stream. Only the volume of air moved directly in the central stream is considered. A standard screen is described, 15 ft. \times 15 ft. \times 10 ft. high, with the top covered except for the blade sweep and the bottom 1 ft. 6 ins. from the ground. An outer screen, 3 or 4 ft. beyond the inner screen, extends from the ground to at least 10 ft. high. The test plane is 5 ft. below the blades, and a 3-in. low velocity type rotating vane anemometer is used to measure the air flow at points on the diagonals of the screen $1\frac{1}{2}$ in. each side of the fan axis and at intervals of 3 ins. in each direction, the area explored extending to a circle of twice the blade diameter. By taking the time for the movement of 1 000 ft. of air at each point the air moved in each annulus can be calculated, and thus the total air movement discovered and the 'Service Value' determined.

B.S.S. 380 is concerned with small diameter high-speed propeller fans of the desk type, with blade sweeps up to 16 ins. The fan is mounted so that there are no obstructions within 6 ft. on the delivery and 3 ft. on the intake sides. Power taken by the oscillating gear is measured by readings with and without it in operation, and must not exceed 5 % of the total taken by the fan. Tests are taken with the

* As the demand for ceiling and desk fans is largely from India, opinion from that country was fully consulted; and one of the authors (Mr. Meares) was a member of the B.S.I. sub-committee.

fan fixed. Air velocities are read by a 3-in. medium-velocity type rotating vane anemometer at points $\frac{3}{4}$ in. each side of the blade axis and at points along a horizontal line at increments of $1\frac{1}{2}$ ins. until a reverse reading is found. Each reading is the time taken by an air movement of 1000 ft. unless more than 2 mins. Thus the average velocity over each annulus can be calculated and the total ascertained.

Specimen calculations are set out in Appendices to both these specifications. Precautions required include the elimination of extraneous air currents and heating apparatus; and the fans are to be run for 1 hr. before readings are taken.

Standard nomenclature and test methods are laid down in the Report of the Committee of the Heating and Ventilating Engineers. The conditions in each case should approximate to those for which the fan was designed. It suffices to test at one speed. For a particular duty, the volume per minute may be taken to vary directly as the speed; the velocity head, resistance head and total fan head vary as the speed squared; and the power varies as the cube of the speed.

1037. Testing the Wiring of an Installation.—The various types of wiring systems available for the supply of electricity to domestic and industrial apparatus are described in §§ 533 *et seq.*, Vol. 2, and model specifications are there given. Tests to confirm the accuracy of the connections of such wiring and of its ohmic resistance are seldom necessary, though the former are desirable in the case of complicated motor control systems and so forth; they consist of simple checking of the various circuits one at a time, by means of a dry battery and bell or lamp. Tests for insulation resistance are, however, necessary in even the simplest installation, and the *I.E.E. Regulations for the Electrical Equipment of Buildings (Wiring Rules)* include a section (127, Ninth Edition) on the subject.

The specific requirements are prefaced by a note to the effect that the tests specified are intended to ensure that the installation is in a satisfactory state at the time of completion. The value of systematically inspecting and testing apparatus and circuits cannot be too strongly urged, and such periodical tests are essential if the installation is to be maintained in a sound condition and undue deterioration detected. All defects thus discovered should be made good without delay.

Before an installation is permanently put into service the *I.E.E. Regulations* require the following tests :—

The insulation resistance shall be measured by applying between earth and the whole system of conductors or any section thereof, with all fuses in place and all switches on, a D.C. pressure of not less than twice the working pressure. Where the supply is derived from a three-wire (A.C. or D.C.) or polyphase system the neutral of which is connected to earth either direct or through added resistance, the working pressure shall be deemed to be that which is maintained between the outer or phase conductors and the neutral.

The insulation resistance of an installation measured as in the preceding paragraph shall not be less in megohms than 25 divided by the number of points on the circuits, provided that : (1) Any installation shall not be required to have an insulation greater than 1 megohm; (2) Lighting circuits shall be tested with all

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lamps in place, except in the case of earthed concentric wiring systems; (3) Heating and power circuits, with or without lighting points, may be tested, if desired, with the heating and power appliances disconnected from the circuits, but with the lamps (if any) in place; (4) The insulation resistance between the case of framework and every live part of each individual dynamo, motor, heater, arc lamp, control gear or other appliance shall not be less than that specified in the appropriate British Standard Specification or, where there is no such specification, shall not be less than 0.5 megohm.

A note is added that, in addition to the foregoing tests, it is advisable, wherever practicable, to take an insulation test between all the conductors connected to one pole or phase and all the conductors connected to the other pole or phase of a system.

The Regulations also provide that the metal conduits or metallic envelopes of cables, in all cases where such methods are used for the mechanical protection of electrical conductors, shall be tested for electrical continuity, and the electrical resistance of such conduits, measured between a point near the main switch and any other point of the completed installation, shall not exceed 2 ohms. Suitable simple testing instruments are available for making this test, without involving any calculations or delicate adjustments.

Tests of the earthing of conduit or other equipment are not given in the Ninth Edition of the *I.E.E. Regulations*, but it is stated that they may be included in a later edition. The satisfactory testing of an earth plate requires the provision of a second alternative earth; given this, the test is readily effected by passing a known current from one plate to the other and observing the voltage drop. Difficulties due to polarisation can be avoided by using A.C., and a simple portable earth testing set is available employing this precaution. The apparatus resembles an insulation testing set. See also §§ 347, 348, Vol. 1.

For the satisfactory testing of an earth plate, Evershed and Vignoles recommend the provision of two additional temporary earth connections. Current is then passed between the plate under test and the further temporary earth connection, the potential drop being measured between the plate under test and the intermediate temporary earth connection. The "Megger" earth tester (§ 119, 5th edn.) comprises an ohmmeter and a special generator which provides A.C. for the earth circuit, while D.C. is used in both coils of the ohmmeter.

1038. Bibliography.—(See explanatory note, p. 58, Vol. 1.)

OFFICIAL REGULATIONS.

The testing of wiring is covered by *Regulations for the Electrical Equipment of Buildings*, issued by the Institution of Electrical Engineers, and better known as the *I.E.E. Wiring Rules*. Government Departments and Consulting Engineers usually specify the tests to which electrical machinery is to be subjected when purchasing.

STANDARDISATION REPORTS.

I.E.C. Publications.

No. 46.—Rules for Acceptance Tests for Steam Turbines.

British Standard Specifications.

- No. 223.—Electrical Performance of High Voltage Bushing Insulators.
 No. 269.—Methods of Declaring Efficiency of Electrical Machinery
 (excluding Traction Motors).
 No. 353.—Testing of Hydraulic Turbines.
 No. 358.—Measurement of Voltage with Sphere-Gaps.
 No. 367.—Performance of Ceiling-Type Electric Fans.
 No. 380.—Performance of Desk-Type Electric Fans.
 No. 406.—Apparatus for Workshop Testing of Permanent Magnets.
 No. 422.—Transformer Inter-Turn Insulation.
 No. 443.—Testing of the Zinc Coating on Galvanised Wires.

In general, all B.S. Specifications contain clauses relating to the testing of materials, apparatus, etc.; reference should therefore be made to the specifications mentioned in the Bibliographies appended to chapters of this book dealing with the equipment concerned.

Books.

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 D.C. Dynamo and Motor Faults, R. M. Archer (Pitman).
 Direct and Alternating Current Manual, F. Bedell and C. A. Pierce
 (Constable).
 Handbook of the Electrical Laboratory and Test Room, Sir J. A. Fleming
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 Earle (Constable).
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 Practical Testing of Electrical Machines, L. Oulton and N. J. Wilson
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 Testing, Fault Localisation, and General Hints for Wiremen, J. Wright
 (Constable).
 Electrical Testing for Telegraph Engineers, J. E. Young (Benn).
 Testing of Continuous Current Machines, C. F. Smith (Pitman).
 Testing Transformers and A.C. Machines, C. F. Smith (Pitman).
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 Insulation Testing and Earth Testing; useful practical handbooks pub-
 lished by Evershed & Vignoles, Limited, London, W. 4.

I.E.E. PAPERS.

- Field Tests on the 'Grid' Transmission Lines, J. S. Forest. Vol. 70, p. 85.
- High Voltage Precision Measurements, W. M. Thornton. Vol. 69, p. 1273.
- Losses in D.C. Machines from No-Load Tests, R. G. Isaacs. Vol. 69, p. 1303.
- A Resistor for the Measurement of Large Direct Currents, E. H. Rayner. Vol. 69, p. 1155.
- An Electrical Method for Determining the Moment of Inertia of a Direct Current Armature, J. C. Prescott. Vol. 69, p. 1179.
- The Electrical High-Pressure Testing of Cables and the Localisation of Faults, J. Urmston. Vol. 69, p. 983.
- The Calibration of Four-Terminal Resistance Standards with Alternating Current at Power Frequencies, A. H. M. Arnold. Vol. 69, p. 1013.
- The Use of Air Condensers as High-Voltage Standards, B. G. Churcher and C. Dannatt. Vol. 69, p. 1019.
- The Design and Construction of a Shielded Resistor for High Voltages, R. Davis. Vol. 69, p. 1028.
- Short-Duration Temperature Testing of Electrical Machines, W. E. French. Vol. 69, p. 867.
- Sphere-Gap Calibration, S. Whitehead and A. P. Castellain. Vol. 69, p. 898.
- High Voltage Testing Equipments, E. T. Norris and F. W. Taylor. Vol. 69, p. 673.
- Dielectric Phenomena at High Voltages, B. L. Goodlet, F. S. Edwards, and F. R. Perry. Vol. 69, p. 695.
- An Investigation of Problems relating to the Use of Pivots and Jewels in Instruments and Meters, V. Stott. Vol. 69, p. 751.
- Dielectric Loss-Angle Measurement of Multi-Core High Tension Cables, with special reference to the Schering Bridge, L. G. Brazier. Vol. 69, p. 757.
- Apparatus and Methods for Accurate Maintenance of Large A.C. Energy Meters, E. Fawcett and G. E. Moore. Vol. 69, p. 647.
- The Electrical Resistance of Moisture Films on Glazed Surfaces, G. T. G. Smal, R. J. Brooksbank and W. M. Thornton. Vol. 69, p. 427.
- Hysteresis Measurements on Straight Bars and Strips, C. E. Webb and L. H. Ford. Vol. 68, p. 1018.
- A New Null Method of Testing Instrument Transformers, and its Application, G. F. Shotton. Vol. 68, p. 873.
- Some Accessory Apparatus for Precise Measurements of Alternating Current, R. S. J. Spilsbury and A. H. M. Arnold. Vol. 68, p. 889.
- Precision Testing of Current Transformers, A. H. M. Arnold. Vol. 68, p. 898.
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- A Method of Testing Current Transformers, W. E. Bruges. Vol. 68, p. 305.

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- Precision Permeability Measurements on Straight Bars and Strips in the region of High Permeability, C. E. Webb and L. H. Ford. Vol. 67, p. 1802.
- The Testing of Porcelain Insulators, B. J. Goodlett. Vol. 67, p. 1177.
- A Precision Electrometer Method of Voltage-Transformer Testing, R. S. J. Spilsbury, Vol. 67, p. 1143.
- Electromagnetic Testing for Mechanical Flaws in Steel Wire Ropes, T. F. Wall. Vol. 67, p. 899.
- Precautions in the Use of Standard Instruments, W. H. Lawes. Vol. 67, p. 541.
- Some Developments in the Routine Pressure-Testing of High Voltage Cables, E. A. Beavis. Vol. 66, p. 1086.
- Testing of Ceiling Fans, E. Hughes and W. G. White. Vol. 65, p. 367.
- The Testing of Static Transformers, J. L. Thompson and H. Walmsley. Vol. 64, p. 505.
- The Rise and Distribution of Temperature in Small Electrical Machines, E. Hughes. Vol. 62, p. 628.

MISCELLANEOUS.

X-Ray Testing Technique is dealt with in 'Methods of Research in Metallography,' by Masing, *Inst. of Metals Jour.*, Vol. 42, p. 69.

Useful articles in periodicals include the following:—

Wattless-Load Alternator Tests. *El. Rev.*, Vol. 107, p. 407.

Progress in Cable Technique, P. Dunsheath. *El. Times*, Vol. 79, p. 216.

Electrical Porcelain, Gillett. *Electrician*, Vol. 105, pp. 434, 538.

Tests on Protective Gear, Wilson. *World Power*, Vol. 15, p. 17.

Acceptance Tests of Turbo-Generators, Eccles. *El. Times*, Vol. 76, p. 297.

Magnetic Testing of Turbo-Generator Rotors, Bailey and Juhlin. *Engg.*, Vol. 130, p. 242.

Testing H.T. and L.T. Insulators, Carr. *El. Times*, Vol. 77, p. 430.

Testing H.T. Cables, Beavis. *El. Times*, Vol. 77, p. 1078.

Sine-Wave Alternators for Meter Testing. *Engg.*, Vol. 128, p. 230.

New Oil Circuit-Breakers of High Rupturing Capacity. *El. Times*, Vol. 78, p. 85.

Important reports are issued from time to time by the British Electrical and Allied Industries Research Association. Hitherto most of these Publications have dealt with the testing and properties of electrical insulating materials, the heating of buried cables, methods of laying cables, the service performance of electrical material and equipment, and interference between power and communication circuits.

CHAPTER 41.

THE LAW: STATUTORY AND OTHER REGULATIONS AND RULES.

The Law and Official Rules.

1039. Scope of Chapter.—Official rules and regulations naturally have an important influence on electrical engineering practice. Though they do not always or necessarily produce the best practice—either from the point of view of economical construction or from that of efficiency in operation—they are, as framed and enforced in the United Kingdom, successful in securing a high degree of safety. Part of the price of this is naturally some hampering of technical developments, but, during recent years, the authorities responsible have shown greater willingness to modify regulations where these can be shown to obstruct developments that would not be inimical to safety. In addition, electrical engineers have voluntarily adopted a number of rules, specifications, and the like framed either by engineering institutions or by groups from among themselves.

Notwithstanding this fact, there appears to be a surprising amount of ignorance concerning the existence and scope of particular rules and regulations; this chapter therefore presents a brief general analysis of the law and of the regulations, etc., bearing upon electrical work. The notes are only intended to form a general guide to the subject, complete presentation of which would occupy a large volume, while the interpretation of the statutory measures is, in most cases, a matter for lawyers alone. It is obviously desirable that every electrical engineer should have general knowledge of the rules and regulations bearing upon his work; of the various professional organisations formed to consider technical problems; and of the specifications and similar publications issued by such bodies. General knowledge of this kind should be supplemented by careful study of the full text of the regulations, etc., bearing upon particular branches of electrical work.

1040. General Scope of Acts, Regulations, Rules, etc.—

The Statutes and other measures framed during the past forty years for the control of the generation, distribution, supply, and use of electrical energy may conveniently be considered under the following heads:—

- (a) The 'Electricity Supply Acts,' under which 'Orders' are granted to 'undertakers,' authorising them to supply electricity in stated 'areas of supply' (§ 1041).
- (b) Local Acts of Parliament dealing with particular areas (§ 1042).
- (c) Provisional Orders, subsequently confirmed by Parliament; Special Orders; and the 'Electric Lighting (Clauses) Act,' 1899 (§ 1043).
- (d) Special Acts and Power Acts (§ 1044).
- (e) Temporary and Emergency Acts (§ 1045).
- (f) Approval of Systems of Supply (§ 1047).
- (g) Regulations of the Electricity Commissioners, under the Electricity (Supply) Acts (§§ 1048 and 1049).
- (h) Home Office (Electricity) Regulations for Factories and Workshops, under those Acts (§ 1050).
- (i) Home Office (Electricity) Regulations for Mines, under the Mines Acts (§ 1051).
- (j) Ministry of Transport Regulations for Tramways and Light Railways (§ 1052).
- (k) Non-statutory Rules governing Electrical Installations in Buildings and Ships (§ 1054).
- (l) Non-statutory Standardisation Rules and Specifications (§§ 1055 to 1057).

In the following paragraphs these measures are discussed in the order and grouping given above.

Sandwiched in its appropriate place is a paragraph dealing with the administration of the law generally (§ 1046).

1041. The Electricity (Supply) Acts, 1882 to 1926.—These, which from the legal point of view are all taken together, comprise:—

- (i) The Electric Lighting Act, 1882;
- (ii) The Electric Lighting Act, 1888;
- (iii) The Electric Lighting (Scotland) Act, 1890;
- (iv) The Electric Lighting Act, 1909;
- (v) The Electricity (Supply) Act, 1919;
- (vi) The Electricity (Supply) Act, 1922—not applicable to Ireland;
- (vii) The Electricity (Supply) Act, 1926—not applicable to Northern Ireland.

Each of these measures to some extent modified the provisions of its predecessor, especially the last and most important one. A sketchy précis of the provisions would be worse than none, and space does not allow of a full one; the reader is referred to the

books * mentioned in the footnote. Here, without going into any detail, the general trend of these Acts will be given as a sign-post.

(i) *The Electric Lighting Act, 1882*.—This first measure was based largely on legal practice relating to other public utilities, especially gas, many provisions from the Gas Acts being incorporated and others drawn upon. The Act gave the Board of Trade (now the Electricity Commissioners) power to grant 'Provisional orders' to 'undertakers' to supply energy in small areas, mostly limited to the jurisdiction of a single local authority. The local authority (if a company was undertaker) was given power to purchase the undertaking after a ridiculously short period and to all intents at scrap value. These Orders required confirmation by Parliament, but could, in certain circumstances, be revoked by the Board—and hundreds were revoked.

Nearly all the technical provisions were contained in each Order (§ 1043) instead of in the Act; and power was further given to the Board to make both Rules and technical Regulations regarding each Order (§§ 1043 to 1045). Further provisions dealt with accounts of undertakers and their submission for audit (in view of valuation before ultimate purchase); with many restrictions and some facilities as to works, both of the undertakers and of other parties, especially works in public streets, such as mains; with charges for energy, coupled with a ban on undue preference or discrimination in making these charges; with offences of, or against, the undertakers; with the incorporation of clauses from the Land Acts and Gas Acts; and with protective clauses. The fatuous provisions as to compulsory purchase made the Act almost a dead letter, and put Great Britain behind other nations for a generation after the electrical era began; and the short-sighted restrictions as to overhead lines and areas of supply, designed so as to make municipal purchase easy, has had the effect of making electricity expensive to the consumers to the present day.

(ii) *The Electric Lighting Act, 1888*.—It took the Government of the day only six years to discover what was obvious to business men in six weeks, namely, that no progress was possible under the first ill-starred attempt at controlling a new industry by a strangle-

* *The Law relating to Electric Lighting, Power, and Traction* by Shiress Will, 5th edition, by John C. Dalton. *The Electricity (Supply) Act, 1926*, by John C. Dalton. Also the annual Digest in the *Electrician*, 'Electrical Trades Directory and Handbook.'

hold. The Act of 1888 was then passed to amend that of 1882 by making the period, after which compulsory purchase could operate, 42 years instead of 21 and by slightly improving the terms of purchase. As a sop to the opposition of the local authorities, however, their consent was at the same time made necessary (subject to the Board of Trade dispensing with it) before an Order could be granted. The bargaining power thus given further delayed progress; for the Municipalities would not embark on supply for fear of loss, nor let companies do so for fear of profit. The opportunity was also taken to put restrictions—rightly—on non-statutory lines and works, which became subject to Regulations (§ 1049); for enterprising companies started supply businesses without any statutory powers, relying on private bargaining for permission to place their mains under or over streets, private land and on houses, to the danger of the public and of the telegraph system.

(iii) *The Electric Lighting (Scotland) Act, 1890*.—This calls for no comment.

(iv) *The Electric Lighting Act, 1909*.—Although good progress was made in the business of electric supply after the passing of the 1888 Act, the defects in the law were very marked; and in 1909 a half-hearted endeavour was made to place matters on a better footing. A Joint Select Committee of both Houses of Parliament under Lord Cross had, in 1898, submitted a Report on 'Electrical Energy (Generating Stations and Supply)' which made far-reaching suggestions, many of which have since been adopted; especially that larger areas of supply were desirable, in consequence of which change in policy many 'Power Companies' came into being (§ 1044). The Act of 1909 was mainly a belated endeavour to correct some of the more glaring anomalies of the earlier Acts. Provision was made, *inter alia*, for the compulsory acquisition of land for generating stations; for breaking up streets outside an area of supply in order to connect up to a generating station at some more convenient place outside that area; for supply 'in bulk' by undertakers to other undertakers known as 'authorised distributors'; for the delivery of a supply at a point within the area for use outside that area, which had been declared illegal by the Courts; for the formation of Joint Committees or Boards by two or more local authorities; together with a number of minor changes. The most important change was that dealing with bulk supply, generally effected under a 'Special Act.'

(v) *The Electricity (Supply) Act, 1919*.—After a further ten years (and the Great War) a radical departure was made in administration by the appointment of the Electricity Commissioners under section 1 of the Act of 1919 and the transfer of the powers of the B.O.T. to the Minister of Transport and the Commissioners. Many of the other provisions of this Act have been modified or repealed by subsequent legislation. The reorganisation of the whole parochial basis of supply was aimed at, by making 'Electricity districts' and constituting 'joint electricity authorities'; and a considerable part of the Act deals with the powers and duties of the latter in relation to supply. The absurd prohibition of 1882 against undertakers associating together for their common ends was modified, as the fear of monopoly vanished; and a beginning was made in the direction of allowing the use of overhead lines and obtaining way-leaves for them. Municipal trading in electric apparatus was made lawful. The Commissioners were given power to demand changes in 'the type of current, frequency or pressure' in the direction of standardisation, which by this time had shown itself desirable and even necessary. 'Special Orders' of the Commissioners, confirmed by the Board of Trade (later by the Minister of Transport) instead of by Parliament, were substituted for the earlier Provisional Orders. Power to demand the submission of statistics of supply undertakings was given to the Commissioners, whose Reports now contain a summary of these relating to units generated, fuel of various sorts consumed, units sold, etc. Many railway and tramway authorities have voluntarily sent in similar statistics, which are incorporated with the others and increase their value. Various new definitions and other matters of less importance are dealt with in the Act; but it was sadly mutilated during its passage through Parliament.

(vi) *The Electricity (Supply) Act, 1922*.—This Act consists largely of financial and other provisions for facilitating the work of Joint Electricity Authorities, together with modifications of the Act of 1919. Of technical interest is the section making 'stand-by supply' subject to conditions as to minimum annual payments; for hitherto a person having a private plant could legally demand a connection to the undertakers' mains without any intention of using a single unit from them except in consequence of a breakdown.

(vii) *The Electricity (Supply) Act, 1926*.—It had long been

apparent that mere tinkering with the basic Act of 1882 and its successors would never give the country 'a cheap and abundant supply of electricity.' As already mentioned, Lord Cross's Committee * recommended the adoption of larger areas of supply; Sir James Kitson's Committee † endorsed this view when the Power Bills were before the Legislature. In 1917 the Coal Conservation Committee and the Electric Power Supply Committee had urged the common-sense aspect of the problem; and the emasculated Statute of 1919 had been intended to tackle their recommendations, but failed to do so.

In 1925 yet another Committee, presided over by Lord Weir, ‡ dealt exhaustively with the subject. Although the recommendations of the Weir Report were turned inside out as time went on, they are broadly incorporated in the Act of 1926. The useful political cry of cheap electricity to the consumer has long since joined other slogans equally dishonest; but the measures undertaken will certainly improve the situation in many ways, less showy but equally valuable to the country.

Broadly speaking, the underlying principle is that the Commissioners shall prepare schemes covering each of the large areas into which Great Britain is divided and that the newly constituted 'Central Electricity Board' shall carry out these schemes as undertaker-in-chief; the large areas being eventually interconnected (at enormous expense, and with very doubtful advantages) by a 'grid' of 132 kV transmission lines. § Generation is to be confined to a small number of super-stations of the most modern and efficient type; the best of these 'selected stations' will work as 'base-load' (or 'three-shift') stations, continuously, on a *plant* load-factor approaching 100 %; || while the next best but some-

* Report of the Joint Committee on Electrical Energy (Generating Stations and Supply), 1898-99.

† Report of the Committee of the House of Commons considering the first 'Power Bills,' 1900.

‡ Report of the Committee appointed by the Minister of Transport 'to review the national problem of the supply of electrical energy and to present a report on the broad lines of policy which should be adopted to ensure its most efficient and effective development.'

§ The same pressure will be used in the necessary inter-connecting grids of transmission lines within each of the areas.

|| It seems to the authors unlikely that the *station* load factor of the base-load stations will be above 70 %.

what less efficient will constitute 'peak-load' stations, to be used for one or two shifts as required, and as reserve against breakdowns. In this way not only will a number of separate stations and staffs be dispensed with altogether, but the proportion of spare plant to total plant, now inordinately high,* will be greatly reduced. The activities of all the stations will be controlled by the Board's organisation of load-despatchers so as to obtain the most economical results; the whole output will be taken over wholesale, on the terms given in the Act, and the Board will re-sell to authorised distributors as well as to the undertakers from whom it was purchased, whether authorised distributors or not.† Complicated provisions are made as to ascertaining costs of production and adjusting them to load factor, the long-established principle of differentiating between fixed kilowatt charges and running charges‡ having at last been recognised by the authorities. As a necessary corollary, further standardisation (especially of frequency) will be enforced, so as both to render inter-connection by the 'grid' possible and to enable manufacturers to standardise motors and other apparatus (§ 1047).

Finance plays a large part in the Act, since the Central Electricity Board are authorised to borrow up to £33,500,000 for their purposes. The Board can itself construct generating stations (under Special Order) if they are unable to make suitable arrangements with undertakers; and they are subject to most of the Acts already analysed above. Further provisions as to overhead lines and way-leaves are made. There are also no less than fifteen

* Stated by the Weir Report to be equal to 68 % of the maximum load, over the whole country, instead of (say) 10 %.

† For instance, railway generating stations may be selected.

‡ The Second Schedule to the Act lays down 'Rules for Determining Cost of Production of Electricity at Selected Stations.' The costs, charges, and allowances are divided among six heads, covering all expenditure on revenue account attributable to the station (other than taxes on profits); interest (other than that paid out of capital) at a rate laid down; and an allowance for depreciation. The Seventh Schedule lays down 'Rules for Determining the Fixed Kilowatt Charges Component and the Running Charges Component' of the total costs as ascertained under the Second Schedule. The fixed charge is to be one-twelfth of the amount allocated as fixed costs in any year, divided by the (statutory) average of the monthly maximum demands of that year, adjusted to load factor. Thirty minutes is the period determining the M.D., so as to exclude momentary overloads, etc. The running charge component is the amount of the running costs, divided by the number of units supplied from the station, not those generated.

sections amending the earlier Acts, but the above comments must be taken merely as an invitation to study the full text.*

As these pages were going through the Press, the Report of the Economic Advisory Council's Severn Barrage Committee was published. The Report will be dealt with more fully in the next edition of Volume 1 under 'Water Power' (Chaps. 8 to 10), by which time a decision may have been arrived at. Briefly the Report proves that by itself the barrage power station would not be able to generate energy at as low a rate as a modern super-station, owing to the intermittance due to slack water and to the impossibility of utilising the full power at spring tides by means of plant which would necessarily be idle at all other times. The Committee therefore recommend combining the barrage scheme with a pumping scheme up to an elevated lake, from which power can be drawn at slack water and into which water can be additionally pumped at spring tides. The cost per unit then works out at a less figure than is at present attainable from fuel. It appears to the authors that in these circumstances the more obvious course is to construct the subsidiary pumping plant and Wye reservoir (holding 20-million H.P.-hr. storage), and to operate it from the spare power *now obtainable* from peak-load stations at off-peak times † (§§ 230, 230A).

1042. Local Acts of Parliament.—The Electric Lighting (Scotland) Act, 1902, is not included in the 'Supply Acts' of the previous paragraph. There are also a number of Acts relating to electric supply in the Administrative County of London. For all these, reference must be made to Dalton.‡

1043. Provisional and Special Orders: the Electric Lighting (Clauses) Act, 1899.—While the Acts deal with broad (and sometimes very narrow) principles, all details were left to the Provisional Orders granted to individual undertakers—for procedure by Licence was hardly resorted to. A stock form of Order was soon evolved, but whenever a company applied for an Order there was opposition on the part of the local authority; and all sorts of special clauses were asked for and, sometimes, inserted. In 1899 the stock form of draft Order was rearranged and made into a Schedule of 84 clauses, which the single operative section of the Electric

* The Electricity (Supply) Act, 1926, annotated and explained by John C. Dalton.

† 'Electricity from Pumped Storage,' J. W. Meares, *El. Rev.*, Vol. 112, p. 629.

‡ *The Law Relating to Electric Lighting, Power, and Traction* by Shireess Will, John C. Dalton.

Lighting (Clauses) Act, 1899, enacted should 'be incorporated with and form part of' every future Provisional Order or Special Act, subject to express variations and exceptions. Presumably because an Order ceased to be Provisional on confirmation by Parliament, the term 'Special Order' is actually used in this Act; but the 'Special Orders' of the Act of 1919 [§ 1041 (v)] are different from, and must not be confused with, those of the Clauses Act. The difference is legal rather than practical, for by section 26 of the Electricity (Supply) Act, 1919, the Special Orders of the Electricity Commissioners, confirmed by the Board of Trade—and, later, by the Minister of Transport—took the place of the former Orders; but after the passing of the Clauses Act both types in turn were immensely simplified owing to the unprinted inclusion of all the stock clauses. These may now be briefly referred to.

Any full summary of the 82 operative clauses would take up more space than can be spared, for the Act takes up 130 pages of Will's *Electric Lighting*. There are provisions as to the area of supply and the undertakers' relations with other undertakers; as to security and accounts; purchase and use of land by local authorities; systems and mode of supply. Under the caption 'Works' come ten very complicated clauses dealing with every conceivable contingency in relation to the laying of lines under or on streets, where other authorised persons may also have works capable of being interfered with.* Compulsory works come next, and methods of obtaining the laying down of mains outside the compulsory list of streets. Next come provisions as to sufficiency of supply, the methods of charging for it and the maximum price to be charged. Electric Inspectors, testing, and clauses as to meters follow. Revocation requires six clauses, and there are a bakers' (or publishers') dozen of general miscellaneous clauses to end up with. Later Acts have amended some of the clauses, but they remain the basis of supply Orders, past and present.

1044. Special Acts: Power Acts.—From time to time a few Special Acts were passed, conferring on local authorities or companies powers similar to those given by the more ordinary procedure dealt with above. But until the Act of 1909 was passed there was little real progress. Once the necessity of larger

* So involved are some of these that an Act of an Indian legislature, based on them, was passed containing one with two whole lines of the text omitted!

areas of supply and of supply in bulk to distributors was recognised, the road was open for development; and the Power Companies came into being. Of about 80 special Acts the majority were passed between 1900 and 1904, and some 30 Power Companies operate under them. At that time, however, these new companies, endeavouring to inaugurate really efficient conditions, were hampered because Parliament in its wisdom decreed that they should not be allowed to supply energy within the area of supply of any existing undertaker without that undertakers' consent; so that the towns, which should have been the economic distributing centres of their networks, were excluded from their operations. Later legislation removed many anomalies and has given the Power Companies a chance which they have not been slow to utilise; and the Act of 1926 has at last dealt with the whole problem on broad lines.

Although differing in many respects, the Power Acts have much in common. The Power Company is authorised to acquire land and to construct the necessary stations and other works and to supply energy within a specified area to 'authorised undertakers' and to other persons for power purposes, within certain limits. Maximum prices and dividends are inter-related by a sliding scale. Under this system, a 'standard dividend' and a 'standard price' per unit are fixed, as in gas undertakings; then, before the dividend can be increased above the standard rate the actual price charged per unit must be diminished and *vice versa*. Thus, assume a standard dividend of 10 % and a standard charge of two pence; further, let an increase or decrease of $1\frac{1}{2}$ % above or below the standard charge correspond, inversely, to a decrease or increase of $\frac{1}{2}$ % in the permissible dividend. Then the results would be as follows:—

TABLE 220.—*Example of Sliding Scale.*

Dividend Payable %.	Average Charge Pence Per Unit.
13	1.77
12	1.82
11	1.88
Standard 10	Standard 2.00
9	2.06
8	2.12
7	2.18
6	2.25

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Under this system the consumer benefits *pari passu* with the undertaker and the shareholder, where the business flourishes, while the country at large benefits both directly from income tax and indirectly from industrial progress.

1045. Temporary and Emergency Acts.—Although, like D.O.R.A., some of these war measures are still in force it is unnecessary to do more than mention those dealing with extension of times within which duties had to be performed and temporary increases in statutory maximum charges for supply.

1046. Administration.—The Act of 1919 [§ 1041 (v)] created a new body, the Electricity Commissioners, and vested in them the administration of the Electricity (Supply) Acts, hitherto in the hands of the Board of Trade; so that the Special Orders and most of the Regulations dealing with the subject are now drawn up by them. In the Annual Reports of the Commissioners will be found full information as to their activities, together with many statistics as to the progress in the generation and consumption of electricity, obtained as a consequence of the new powers conferred by the Act in question [§ 1041 (v)].

The Commissioners are authorised to exercise certain powers and to perform certain duties with regard to:—

- (i) The approval of systems of supply adopted by undertakers, in accordance with the provisions of section 10 of the Electric Lighting (Clauses) Act, 1899, or corresponding provisions in any Special Act or Order (§ 1047);
- (ii) The prescribing of Regulations for securing the safety of the public (including subsidiary Regulations as to the construction and maintenance of overhead lines) under section 6 of the Electric Lighting Act, 1882; the Regulations in question, as will be seen (§ 1048), are duplicated, namely, for ordinary and for extra high-tension work;
- (iii) The prescribing of Regulations for ensuring a proper and sufficient supply of electricity by undertakers, under the provisions of section 6 of the same Act (§ 1048);
- (iv) The service of notices and the prescribing of Regulations under section 4 of the Electric Lighting Act, 1888, on non-statutory undertakers, for the protection of the public and of the works of the Postmaster-General (§ 1049).

Other powers of the Commissioners are mentioned in connection with the Act of 1926 [§ 1041 (vii)].

1047. Approval of Systems of Supply.—Certain standard approved systems of supply were set forth in the *London Gazette* of July 3, 1906, and May 8, 1925, and from time to time the Commissioners have added to these in the like manner. A Model Form of description was published by the Board of Trade long ago, for

the use of undertakers desiring sanction for a new system; and the Commissioners took this form over with the rest of the work of the B.O.T. British standard pressures of 11 000, 22 000, and 33 000 volts and the British standard frequency of 50 cycles are now generally adopted, while far higher pressures (up to 132 kV) are used on the new transmission 'grid.' In this connection we may also mention the approval and certification of meters, of which new types are every year put on the market.

1048. Regulations of the Commissioners for Statutory Undertakings.—The Commissioners, when they were appointed, took over all the existing Regulations, etc., of the Board of Trade; but these have been mostly revised and extended since (*but see* §§ 1041 to 1043). The document known as 'El. C. 38,' after defining the terms used, contains the Regulations (A) for Securing the Safety of the Public and (B) for Ensuring a Proper and Sufficient Supply of Electrical Energy. Further Regulations, similarly sub-divided into (A) and (B), are found in 'El. C. 13' as to extra high pressure. Further, under Regulation No. A 13 of the former batch, additional Regulations were made ('El. C. 39') for overhead lines, which until recently were seldom used in the United Kingdom; these, however, were superseded in 1928 by the new 'Overhead Line Regulations for Securing the Safety of the Public,' made by the Electricity Commissioners under the Electric (Supply) Acts, 1882 to 1926, known as El. C. 53, together with an attached explanatory memorandum, El. C. 53 A, and a further memorandum, El. C. 53 B (§ 846). Although long reduced to standard forms these various Regulations were originally made by the Board of Trade for each separate undertaking and attached to the Provisional Order. We will consider these *seriatim*.

El. C. 38 A.—The ordinary Regulations for securing the safety of the public begin with twelve 'General' clauses specifying the permissible pressure of supply to consumers and the precautions to be taken where 'medium pressure' is so supplied, and they also lay down that an 'extra high-pressure' supply, when permissible at all, shall be subject to further Regulations—*vide* 'El. C. 13' below. The size of conductors, the testing and maintenance of their insulation, their protection by circuit-breakers and from lightning and special precautions for transformers follow.

Next in order comes No. 13, giving power to issue further Regulations for overhead wires, as to which see 'El. C. 53' below.

Then there are seven clauses dealing with lines other than overhead, with their street boxes, etc., and a further three dealing with sub-stations and street boxes alone.

Consumers' premises are next dealt with in respect to fire and shock risks, leakage and testing. Finally come precautions where are lamps are used; a clause as to connection with earth; and penalties.

El. C. 38 B.—The ordinary Regulations for ensuring a proper and sufficient supply provide in particular for fixing the 'declared pressure' and 'declared frequency' of supply to consumers, and the permissible variation therefrom; * and, further, for continuity and sectionalising of mains so as to restrict the effects of any inevitable stoppage.

(For special Regulations applying to factories and mines, which do not come under the above, see §§ 1050, 1051.)

El. C. 13 A and B.—The special Regulations for securing safety and ensuring a proper supply where extra high pressure is involved are 'in addition to and not in substitution for the obligations imposed by' the above-mentioned code. They are, *mutatis mutandis*, on much the same lines, though more searching.

El. C. 53.—The Special Regulations for overhead lines deal generally with the material of the conductors, their strength, minimum size, and manner of erection; their supports; their relation to other overhead wires; and their maintenance after erection. Service lines are the subject of a special clause. There are also specific Regulations (A) for pressure not exceeding 650 V direct current or 325 V alternating, and (B) for higher pressures, as to the factor of safety of the line conductors, their minimum height from the ground and precautions to be observed for preventing 'danger' as defined; also, in the case of high pressure, as to the manner of crossing roads, canals and railways. As mentioned in dealing with rural lines in connection with electricity in agriculture (§ 846), these Regulations have to some extent met the objections raised with regard to those they supersede (*El. C. 39*). An Explanatory Memorandum (*El. C. 53 A*) is issued with the Regulations, together with a further Memorandum (*El. C. 53 B*) setting forth the information to be submitted in connection

* As noted in § 846, the allowable variation is increased temporarily for supply in rural districts.

with applications by Authorised Undertakers for the consent of the Minister of Transport to the placing of electric lines above ground.

(For factories, *see* § 1050; mines, § 1051; traction, § 1052.)

1049. Regulations of the Commissioners for Non-Statutory Undertakings.—The Regulations (El. C. 12) issued under § 4 of the Electric Lighting Act, 1888, are technically very similar to those already mentioned above. They are not ‘deemed to authorise the Owner’ (*i.e.* of the non-statutory works) ‘to break up or interfere with any street’—a power conferred by the Act on undertakers only. They prescribe the general conditions and precautions to be observed in installing and maintaining supply circuits, substations, etc., so as to avoid risk of shock, fire or interference with telegraph lines; they specify the material, strength, spacing and manner of erection and maintenance of overhead lines; and they deal with the connection of circuits with earth, both for continuous and alternating currents.

(For factories, mines and traction see the following paragraphs.)

1050. Home Office Regulations for Factories and Workshops.—The Regulations, dated December 23, 1908, made by the Secretary of State, ‘for the generation, transformation, distribution and use of electrical energy in premises under the Factory and Workshop Acts, 1901 and 1907,’ are published as Statutory Rules and Orders, No. 1312, 1908. These have their own definitions, which however do not differ materially from those of the Commissioners; and these are followed by a large number of exemptions. Then follow 32 regulations for ensuring the safety of operatives and laying down the owner’s responsibility for seeing them carried out in a proper manner. In view of the complexity of the conditions, the Senior Electrical Inspector of Factories prepared a Memorandum explaining them (Form 928, third edition, 1925); but it must be understood that even this official Memorandum cannot be regarded as an authoritative interpretation in the eyes of the Law Courts. It should, however, be carefully studied by ‘occupiers, agents, workmen and persons employed’ since all of these have to comply with the Regulations and have varying degrees of responsibility. We cannot here give any useful précis of so varied a collection, and the text must be referred to.

1051. Home Office Regulations for Mines.—The ‘General Regulations as to the installation and use of electricity’ under the Coal Mines Act, 1911, are comprised in ‘Mines and Quarries Form

No. 11,' dated August, 1924. Being part only of the Statutory Rules and Orders dealing with mines and quarries, they begin at No. 117 in the above Form, which also contains an Explanatory Memorandum by the Electrical Inspector of Mines to which the remarks at the end of the preceding paragraph apply. In pursuance of § 88 of the Coal Mines Act, 1911, the Secretary of State has prescribed that the book to be supplied to electricians and assistant electricians employed in and about mines shall contain certain parts of the Abstract and General Regulations; these together with the Home Office Memorandum, are published as Mines and Quarries Form No. 58. The Regulations, Nos. 117 to 137, are in two parts dealing with works (1) below ground and (2) above ground. For reasons of space we cannot abstract these here; they must be studied in detail by those concerned. Certain of them have, however, been quoted in Chapter 32 (Electricity in Mining) and at appropriate points elsewhere in these volumes—*vide* index.

1052. Ministry of Transport Regulations as to Tramways and Light Railways.—There are several sets of these regulations, issued separately, governing the generation and distribution of electrical energy for use on tramways and light railways, and the electrical details of the line equipment and rolling stock. Their nature is indicated by the four brief summaries following:—

- (1) *Regulations made by the Minister of Transport under the provisions of Special Tramways or Light Railways Orders authorising lines on public roads, for regulating the use of electrical power; for preventing fusion or electrolytic action of or on gas or water pipes or other metallic pipes, structures, or substances; and for minimising as far as is reasonably practicable injurious interference with the electric wires, lines, and apparatus of parties other than the Company, and the currents therein, whether such lines do or do not use the earth as a return.*

These have their origin in the Report of Lord Cross's Joint Select Committee of 1893 on 'Electric Powers (Protective Clauses)' and the matter contained in that Report and accompanying evidence is still valuable. The Regulations have been repeatedly revised between 1894 and 1920. They stipulate the use of D.C., but 'the Minister of Transport will be prepared to consider the issue of Regulations for the use of A.C. for electrical traction on application.' The

regulations govern the extent to which the return circuit may be uninsulated; the bonding of the rails and of adjacent uninsulated conductors to the rails; the method of earthing the return circuit; the value of the current passing from the earth connections to the generator; the P.D. between the uninsulated return and any pipes in the vicinity; the potential drop in the uninsulated return; and the tests to be made to ensure compliance. With the insertion of names and dates, and minor modifications as required, these and the following regulations are issued as Statutory Rules and Orders for individual tramways, etc.

(2) *Regulations and Bye-laws made by the Minister of Transport as regards Electrical Power on Individual Tramways.*

These include clauses relating to the provision of speed indicators, brakes, life-guards and lamps; the use of trailers; the provision of doors and accommodation for passengers; the speed of propulsion; the maximum electrical pressure; the support, sectionalisation and insulation of the line; the insulation of conductors on vehicles and the earthing of bare metal parts. A copy of the Regulations and Bye-laws must be posted inside each carriage for public information.

(3) *Memorandum regarding details of Construction of New Lines and Equipment.*

This includes certain clauses from the Regulations (2) above, and stipulates requirements and recommendations as to reconstruction of track, cars and equipment undertaken after the date of the Memorandum, as well as to new lines or rolling stock. In Section I.—Constructional Details—there are clauses relating to the clearance between cars and kerbs, bridges, etc.; the general arrangement of overhead equipment; and the weight, dimensions and slotting of rails. Section II.—Car Equipment—deals with the general arrangement and equipment of the cars.

(4) *Guard Wires on Electric Tramways and Light Railways laid on Public Roads.*

These specify the size and arrangement of guard wires, their earthing, etc., and an explanatory Memorandum is attached.

NON-STATUTORY RULES AND STANDARD SPECIFICATIONS, ETC.

1053. Bodies which Issue Rules, Specifications, etc.—
Almost every professional organisation, trade and manufacturing

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association, issues from time to time some documents akin to the official regulations dealt with above, either with some semblance of power to enforce them or merely for guidance. We cannot pretend even to touch on all these; but some of the organisations of outstanding importance are mentioned in the following paragraphs. These are, the Institution of Electrical Engineers (§ 1054); the British Standards Institution (§ 1055); the International Electrotechnical Commission (§ 1056); the World Power Conference (§ 1058); the British and Allied Electrical Manufacturers' Association (§ 1059).

In addition to the above there are many more which need merely be mentioned here. The London County Council issues a number of regulations applicable to electrical installations in the London area, and many municipal undertakers issue similar codes; but the Incorporated Municipal Electrical Association, representing 231 of these, has adopted the I.E.E. Regulations (§ 1054) as standard practice and has recommended their use. So, too, have nearly a hundred of the leading Fire Insurance Companies, thus replacing the Phoenix Co.'s rules, which for many years were in healthy rivalry with those of the I.E.E. Nearly all company undertakers still issue their own installation rules, some of which appear to conflict with the law, though they are useful as a check on the jerry-wireman. Perhaps the most important in all these is the provision limiting the current which may be taken from one side only of a 3-wire D.C. or 3-phase system, so as to ensure that other consumers' supply will not be interfered with.

1054. The Institution of Electrical Engineers.—The I.E.E. issue four documents of special importance, namely:—

- (i) The Model Form of General Conditions for Contracts.
- (ii) The Clauses for Street Lighting Specifications.
- (iii) The Regulations for the Electrical Equipment of Buildings, generally known—and quoted in these volumes—as the 'I.E.E. Wiring Rules.'
- (iv) The Regulations for the Electrical Equipment of Ships.

(i) *Model Form of General Conditions.*—This model is intended to supersede the multiplicity of general conditions issued by consulting engineers and others in the past, and often even now, to rule the legal side of engineering contracts. The general adoption of the code, which has undergone many revisions and much criticism, is highly desirable in the interests of standardisation and uniformity. The Form is obtainable from the Institution

and has been referred to in § 534 and also in various other places in these volumes (*vide* Index).

(ii) *Clauses for Street Lighting Specifications*.—The above remarks on the Model Form apply here also (*see also* § 534). It may be mentioned that the B.S.I. has recently also issued a Street Lighting Specification.

(iii) *The 'I.E.E. Wiring Rules'*.—These originated as far back as 1882. When Vol. 1 of this work was issued the seventh edition (1916) was in force, and in § 525 of Vol. 2 the revised corresponding regulations of the eighth edition (1924) were set forth. At the time of writing, the ninth edition (1927) is the latest; but in a note we find:—

'This edition, which does not differ considerably from the eighth, contains a number of alterations which had become urgent. A tenth edition is in preparation, which, with a view to simplification, may differ materially from the ninth in respect of arrangement and wording.'

In view of this, and of the growing bulk of the Regulations (128 pp., 128 rules, tables and appendixes), we can do no more than point out how the land lies; the volume can be obtained from the Institution.* In our index entries are, for uniformity, all under 'Wiring Rules of the I.E.E.' While the regulations are mainly concerned with internal wiring, generating plant and motor installation also find a place.

(iv) *I.E.E. Regulations for the Electrical Equipment of Ships*.—The conditions as to wiring and installation work generally differ materially between building and ships. A Committee of the I.E.E. has long existed for dealing with this special problem and these Regulations are the result (§ 966). The second edition was published in 1926 and runs to 115 pages and 127 Rules.

1055. The British Standards Institution.—This body, now always known as the B.S.I., started life in 1901 as the Engineering Standards Committee, under the auspices of the four Institutions of Civil, Mechanical and Electrical Engineers, and of Naval Architects, together with the Iron and Steel Institute. It was incorporated as the British Engineering Standards Association (B.E.S.A.) in 1918, and under its present title in 1931; and particulars of its activities and its many publications can be

* *Regulations for the Electrical Equipment of Buildings*, ninth edition, May, 1927. The Institution of Electrical Engineers. The issue of the tenth edition is imminent (1933).

obtained from the office.* At one time it was the custom of each manufacturer to avoid any semblance of standardisation, so as to prevent interchangeability with the apparatus of his rival; thus each had his own bastard threads and so forth; but the value of co-operation in place of insensate rivalry has long been recognised. The B.S.I. has, up to date, issued over 500 Specifications and Reports, many of which constitute miniature text-books, and all of which should be studied by practical engineers. These specifications (which include methods of testing materials and apparatus) are constantly incorporated in specifications for particular works, and should be conformed to whenever possible. They are issued at a price of two to five shillings each, and in many cases translations are available in Continental languages. Revision is undertaken as often as required, to meet technical advances. A complete list of the latest issues can be obtained from the Institution (C.C. 7822), so we need not print it here; but we may mention the 'Standardisation Rules (Export) for Electrical Machinery and Transformers' intended to facilitate competition with manufacturers abroad. Reports and Specifications bearing on the subject-matter of particular chapters will be found in the Bibliographies at the end of each chapter.

1056. The International Electro-technical Commission.—This body, familiarly known throughout the world as the 'I.E.C.,'† was formed in 1906, when it began the preparation of statutes (not in the legal sense) which contemplate the formation of electro-technical Committees in all self-governing countries and provide for the representation of these national committees on the International Commission. The general purpose is to standardise nomenclature and ratings for electrical apparatus and machinery and to agree upon fundamental standards on which national specifications may be based, adapted to the local conditions. A good deal of useful work has been done, but naturally it proceeds slowly; and apart from the purely technical work, the gathering together of delegates from forty or more nations, bent on exchanging views, is of unquestionable value, as one of the Authors (representing India) can testify. Many national committees are in being; while countries that are unable to form these may nevertheless be repre-

* 28 Victoria Street, London, S.W. 1.

† Also located at 28 Victoria Street, London, S.W. 1.

sented by delegates. The agreed international letter and graphical symbols are used in these volumes; the standard of resistance for copper is universally used; but on matters such as the rating of machinery there is still some difference of opinion. However, between the B.S.I. and the I.E.C. the good work proceeds.

1057. The International Standards Association.—At the end of 1927 a new body, the International Standards Association or I.S.A. came into being, as the result of the deliberations of the 'Committee of Seven' held at the New York Conference of 1926 and in London in 1927. The object of the new body is to carry on the work of standardisation in cordial relations with other similar bodies, especially the I.E.C., in matters beyond the scope of those other bodies. The office is temporarily located at 28 Victoria Street, London, and Sir Richard Glazebrook is the first President.

1058. The World Power Conference.—This comparatively new organisation* held its first congress during the Wembley Exhibition, and thereafter published four stupendous volumes of papers and discussions on every phase of power production and utilisation. It has not so far branched out into rules (except as to its own constitution), but is mentioned here because its work is more or less parallel to that of the bodies dealt with in the preceding paragraphs. Among its activities it took up the question of the rating of rivers for hydro-electric development, on the initiative of one of the present Authors, and this subject has since been transferred to the I.E.C.—which in the aforesaid Author's opinion is far less likely to come to a decision on it within reasonable time.† A Fuel Conference under the auspices of the W.P.C. was also held in 1927.

* 68 Lincoln's Inn Field, London, W.C. 2.

† This question was not mentioned in Chaps. 8 to 10 (Water Power) as it had not then arisen, but it is of sufficient importance to find a place here. The papers presented to the First World Power Conference included a complete set dealing with the water-power resources of all the countries represented; but the estimates were based on no standard system and were not directly comparable. Mr. J. W. Meares was asked to write a paper summarising the statistics, and this was published in the Journal *World Power*, Vol. 3, No. 13, January, 1925. The estimates were given (i) in kilowatts; (ii) in electrical horse-power; (iii) in turbine horse-power; (iv) in theoretical water horse-power; (v) from run-off and altitude; (vi) in actually developed and installed power, which is of course often far in excess of the continuously available 24-hr. power. After applying various factors a total of 138 million kW was found; but a plea was made for agreement on a common basis in future, and this is now being sought. See index 'Rating of rivers.'

1059. The British and Allied Electrical Manufacturers Association (B.E.A.M.A.). The B.E.A.M.A., as it is invariably known, aims at establishing a high and uniform standard in the commercial and technical practice of members of the Association; and its publications deal largely with these matters. Among them may be mentioned a series of leaflets on 'Conditions of Sale' of goods in the United Kingdom and abroad; a series of Manufacturers' Purchasing Specifications; and a number of 'Standardisation Rules for Electrical Machinery' dating from 1913, which may profitably be read in conjunction with the B.S.I. and I.E.C. Reports and Specifications. They cover a very wide range, and overlap in many cases matters in which the I.E.C. has also done much spade work.

1060. Bibliography.—(See explanatory note, § 58, Vol. 1.)

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